CONTROL OF STACK EMISSIONS USING HYDRATED LIME INJECTIONS DURING INCINERATION OF HEALTHCARE RISK WASTE: A CASE STUDY OF BIOMED IN BENONI

by

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Dedication

I dedicate this study to myself, my kids and all women in abusive marriages and relationships. After escaping an abusive marriage, myself, I realised that I am not defined by my past but I am who God says I am. I am strong, smart, intelligent, beautiful and I'm a black woman.

Declaration

Student number: 4727 707 6

I Nomathemba Themba, hereby declare that the dissertation herewith on the subject **Control of stack emissions using hydrated lime injections during incineration of healthcare risk waste: A case study of Biomed in Benoni**, is my own work and has not previously been submitted by me for a degree at this or any other institution.

I declare that all the sources used and cited in this dissertation have been indicated and acknowledged by means of complete referencing.

I declare that the final copy of my dissertation has been submitted through Turn-it-in electronic plagiarism detection programme and it met all the requirements.

Student signature

02 January 2020

Date

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Abstract

Incineration is still a widely utilised method for treating healthcare risk waste in the Republic of South Africa. As much as incinerators are needed, the fact that they are still a critical source of hazardous toxic air pollutants that are not easy to manage cannot be disregarded. The Ministry of Environmental Affairs has promulgated a new regulation for General and Hazardous Waste Thermal Treatment. This exceedingly stringent air pollution legislation requires that existing incinerators be modified or redesigned to meet the new air quality standards, or face closure in the event that they fail to comply. The regulation contains strict emission requirements for concentrations of stack gases such as CO_2, NO_2, NO_x, HCl, HF, CO, SO_2, as well as TOC and PM. To be certain that emissions are within the standard, incineration facilities are instructed to reduce the acid gas emissions and to have permanent on-line monitoring equipment for stack testing of regulated pollutants.

Since the promulgation of the new legislation in April 2015, none of the incinerators in South Africa has been able to achieve the new requirements**.** This study, based on the quantitative approach, was conducted in search of a cost-effective method of controlling acid gas emissions from incinerators without major adjustments to the plants. During the study, 60 kg of sorbacal $Ca(OH)_2$ was injected into a lime feeder every day. A variable speed drive was used to inject $Ca(OH)_2$ into the furnace continuously at a rate of between 2.5 kg/h and 3.5 kg/h. The temperature was maintained between 850°C and 1200°C with the use of four gas burners. Two manual blowers were utilised to ensure a continuous flow of $Ca(OH)_2$ into the reaction chamber and filtration system.

Comparative analysis was done to compare gas emission levels before and after the use of hydrated lime. Descriptive statistics were used to compute the mean, frequency and percentages, while Wilcoxon sign rank test established whether hydrated lime was significant in reducing gaseous emissions or not. Wilcoxon sign rank test showed a statistically significant difference ($P<0.05$) in the reduction of all gaseous emissions using hydrated lime, except particulate matter where there was a significant increase in emissions.

This technology was able to achieve high removal efficiency of 97% for HCl, 86% for HF, 83% for NO_x, 87% for SO_2 and 74% for NO_2. The optimum temperature for SO_2 and NO_x was 1020°C. For HCl it was between 1190°C and 1200°C, and for NO_2 it was between 1120°C and 1200°C. The amount of particulate matter increased along with the concentration of the $Ca(OH)_2$ injections. $Ca(OH)_2$ was found to be cost effective in the controlling and capturing of gaseous emissions.

It is recommended that combustion requirements, such as heat, oxygen and turbulence, be considered to reduce the amount of gases generated during the incineration of healthcare risk waste. It is also recommended that electrostatic precipitators be used instead of fabric filters to improve the efficiency of capturing the particulate matter.

Keywords: acid gas emissions, dry sorbent injection, gaseous emissions, hydrated lime, incineration of healthcare risk waste, stack emissions

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Acronyms

AEL	Atmospheric Emission Licence
AQMPs	Air Quality Management Plans
$Ca(HO)_2$	Hydrated lime
$CaSO_4$	Calcium sulphate
°C	Degrees Celsius
CEMS	Continuous Emission Monitoring Systems
CO	Carbon monoxide
CO_2	Carbon dioxide
DEA	Department of Environmental Affairs
DSI	Dry sorbent injection
EPA	Environmental Protection Agency
EU	European Union
ESP	Electrostatic precipitators
FGD	Flue Gas Desulphurisation
FTIR	Fourier Transform Infrared
°F	Fahrenheit
GHG	Green House Gases
GN	Government Notice
HCl	Hydrogen chloride
HF	Hydrogen fluoride
HPA	Highveld Priority Area
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardisation
K	Kelvin
Kg	Kilogram
kPa	Kilopascal
MATS	Mercury and Air Toxics Standards
MES	Minimum Emission Standards
NEMA: AQA	National Environmental Management Act: Air Quality Act

NO_x	Oxides of nitrogen
NO_2	Nitrous Oxide
PM	Particulate Matter
RH	Relative Humidity
SA	South Africa
SAAQIS	South African Air Quality Information System
SANAS	South African National Accreditation System
SDIB	South Durban Industrial Basin
SNCR	Selective Non-Catalytic Reduction
SO_2	Sulphur dioxide
SO_3	Sulphur trioxide
SO_x	Sulphur oxides
TOC	Total Organic Compound
USA	United States of America
WHO	World Health Organisation

Chapter 1: Introduction

1.1 Background

Healthcare risk waste is a portion of waste generated at healthcare facilities, such as hospitals, doctors' surgeries, dental practices, blood bank centres, veterinary hospitals, clinics, laboratories, as well as medical research facilities (NEMA Regulation, 2013). Generally, healthcare risk waste contains blood, body fluids, body parts or other potentially infectious materials and is also referred to as medical waste. In view of its infectious nature, it is recommended that healthcare risk waste is treated through the incineration process (Astrup and Riber, 2011). According to NEMA (2004), incineration is any procedure, technique or method that transforms waste to flue gases and by-products by means of oxidation. Wojdyga, Chorzelski & Rozycka-Wronska (2014) have described incineration as a thermal treatment, which transforms the waste into ash, flue gas and heat. During this process, the waste is treated at a temperature between 850°C to 1200°C.

Although the recommended way of treating healthcare risk waste is through incineration, the utilisation of incinerators is still disputable (Vehlow, 2015). The incineration process results in the release of environmental emissions often referred to as stack emissions (Quicker, Rotheut, No€el, Schulten & Athmann, 2014). Stack emissions are those gases and solids that come out of the smoke stack during the incineration process. These are for the most part carbon dioxide (CO_2), nitrous oxide (NO_2), oxides of nitrogen (NO_x), hydrogen chloride (HCl), hydrogen fluoride (HF), carbon monoxide (CO), sulphur dioxide (SO_2) and as well as total organic compound (TOC) calculated as total carbon. Incineration processes reduce the amount of waste that needs to be disposed of at the landfill site, however the process generates acid gases that are released into the atmosphere (Guo, 2012).

Waste products that are incinerated are transformed into ash, gases and heat (Quicker *et al.,* 2014). During incineration of healthcare risk waste, acid gases released contribute to climate change as SO_2 and NO_x play a significant part in global warming and acid rain. The basic sources of acid rain are sulphur and nitrogen compounds from human activities such as power generation, motor vehicles, incinerators and boilers. There are other causes that contribute to climate change, mainly human activities that contribute to air pollution, greenhouse gases, deforestation, burning of fossil fuels and

more (Charity, Shakespeare & Lawrence, 2013). These pollutant emissions contribute to global patterns of greenhouse gas emissions and incineration facilities have been recognised as one of the main causes of these pollutants (Antonioni, Sarno, Guglielmi, Morra & Cozzani, 2011).

Climate change is already eminently influencing the Republic of South Africa in view of uncontrolled gaseous emissions mainly from combustion processes including incineration facilities. This presents a significant risk to South Africa's water resources, food security, health and well-being, infrastructure and ecosystem services and biodiversity (Charity *et al.,* 2013). In a country where numerous individuals are indigent and where levels of social imbalance are high, these impacts of climate change are unfavourable for advancement. Different places are encountering distinctive impacts of climate change and this pattern will worsen in the future. Some areas in Southern Africa will have less rain and more wind; others will have more rain, and it will be hotter and more humid everywhere (Hatfield and Prueger, 2015). It is well known that the atmospheric temperature increases are created by rising CO_2 concentrations and acid gas emissions (Ragazzi, Tirler, Angelucci, Zardi & Rada, 2013).

In 2010 President Jacob Zuma co-chaired with the President of Finland, His Excellency President Tarja Halonen, a 21-member High Level Panel on Global Sustainability created by the United Nations Secretary General (COP21, 2015). This console comprised of leading policy producers who tried to generate a blueprint for accomplishing low carbon security in the 21st Century. One of the items they had to look at was the issue of improving the quality of ambient air in RSA mostly affected by gaseous emissions (COP21, 2015).

The standard of ambient air in many areas of South Africa is not conducive to a healthy environment for the general population. The effects related to polluted ambient air fall most vigorously on destitute individuals. The contamination of air conveys high social, economic and environmental expenses that are rarely borne by the polluters. The minimisation of contamination through stringent controls, cleaner innovations and cleaner production applications are critical to guarantee that air quality is improved. The objective of the National Environmental Management Air Quality Act (NEMA: AQA) is to improve ambient air to ensure an environment that is not damaging to health and well-being. Section 21 of Listed Activities regulation is an imperative stride towards minimisation of pollution through stringent control technologies (NEMA: AQA, 2013).

The previous emission standard for hazardous air pollutants, as stipulated by the old Air Pollution Prevention Act 45 of 1965, was fundamentally higher than the designated safety standards by the World Health Organisation (WHO). The old standard created a significant amount of unreliable and prospective safety hazards for both the environment and general wellbeing. However, that has undergone some changes and a resolution to reduce acid gas emissions is urgently required.

On 24 April 2016 the Minister of Environmental Affairs, Edna Molewa endorsed the Paris Agreement on climate change at the United Nations in New York. The Paris Agreement was embraced on 12 December 2015 at the 21st session of the Conference of the Parties, conducted in Paris from 30 November to 13 December 2015. The Agreement was an inclusive structure, which directed international undertakings to control gaseous emissions and to address all the related difficulties created by climate change (COP 21, 2015). The Agreement encouraged an adjustment in pace towards the low carbon advancement from 2020 ahead through dedications of countries in aggressive national arrangements called Nationally Determined Contributions. According to the Agreement, climate change constitute a critical risk to human societies and the planet, requiring the broadest collaboration by all nations and different partners (COP 21, 2015).

There has always been a stigma associated with incinerators because of their relationship with toxic environmental emissions. However, the fundamental problem for incinerators in RSA started with the new amended Section 21 of National Environmental Management Act: Air Quality Act known as NEMA: AQA 39 of 2004 that requires stack emissions to be reduced almost by half. The new standard was amended on 31 March 2010 but only came into effect on 1 April 2015. The standard affects thermal processes such as waste incinerators, coal plants, steel industries, and boilers. Since the promulgation of the standard, incineration facilities have been reporting non-compliance for environmental emissions. The new stringent standard is to be complied with as per the stack emissions requirements. Nearly all the current incineration facilities in RSA are not able to comply with the new pre-requisites for air quality standards (Sarkar and Sarkar, 2015).

The plant facility owners are required to send their monthly emission reports to the Department of Environmental Affairs (DEA) and to the interested or affected parties such as affected neighbours, Greenpeace, interested non-governmental organisations, and environmental protection organisations. This has led to the

development of a wide range of issues, with residents close to the facilities objecting to the use of incinerators, the air quality officials opting to close down facilities if they do not comply, and the Department of Health always running short of treatment facilities to use for the incineration of healthcare risk waste generated from different hospitals, clinics and laboratories (Sarkar and Sarkar, 2015).

Like other existing incineration facilities in RSA, Biomed Disposal Services is battling to reduce gaseous emissions to meet the required limits. Their gaseous emission findings were five times greater than the authorised limits with HCL reaching 417 mg/Nm^3, CO reaching 200 mg/Nm^3, HF reaching 2 mg/Nm^3, SO_2 reaching 375 mg/Nm^3 and NO_x reaching 289 mg/Nm^3. The organisation endeavoured to alter the loading intervals and maintaining the temperatures at the manufacturer's prescribed levels with the expectation of reducing as many gases as possible; however, the concentrations were still more than the recommended limit (Production reports, 2015).

So far, the preferred method of disposing healthcare risk waste is to incinerate it because non-burn technology cannot treat anatomical and pharmaceutical waste (Roes, Patel, Worrell & Ludwig, 2012). However, there are insufficient treatment facilities taking into account the amount of healthcare risk waste generated nationwide. Gauteng alone has three high-tech commercial incineration facilities, which are all owned and managed by private entities, namely Biomed, Enviroserv and Averda. These facilities become overwhelmed and the waste is then disposed of in an unacceptable manner. Limpopo Province does not have any incineration facilities and it brings its healthcare waste to Gauteng for treatment purposes (Vehlow, 2015).

Currently, the KwaZulu-Natal Department of Health does not have any treatment facility that complies with the new legislation for gaseous emissions due to the inability to maintain and meet the new requirements by the facility owners (DEA, 2013). Durban recently had a problem where healthcare risk waste was washed up along the coast and several beaches had to be closed off during the clean-up. The people responsible for dumping have not been identified as the waste was found in plastic liners not bar-coded containers and could not be traced (The Citizen, 18 May 2016).

With the promulgation of Section 21 of the NEMA: AQA 39 of 2004 most incineration facilities will become liquidated if they do not comply. A comparable situation occurred in the United States of America (USA) with the implementation of the Clean Air Act in 1970. It brought about the closure of numerous incineration facilities in the USA, both large and small because many facility owners could not modify the essential air

pollution control techniques to meet the new requirements for stack emissions standards. It was confirmed that about 105 to 135 facilities were shut down as a result of non-compliance because those facilities were commissioned before the new regulation came into existence (Le Cloirec, 2012).

As much as incineration plants are required for the treatment of healthcare risk waste, it should be noted that incinerators are still a condemnatory base of hazardous toxic air emissions that are difficult to reduce (Roes *et al.,* 2012). Less constant contaminants such as acid gases, like nitrogen oxides (NO_x) and sulphur oxides (SO_x), can still be extremely dangerous and have negative effects on public health at local and regional levels around incinerators. To reduce the emissions below the stipulated limits, studies have been done using hydrated lime [$Ca(OH)_2$] injections which are a cost-effective approach for reducing acid gas emissions (Sewell and Dickerman, 2012). Numerous facilities in the steel industry have utilised $Ca(OH)_2$ to capture the environmental contaminants. Hydrogen chloride reduction utilising $Ca(OH)_2$ has been previously proven (Sewell and Dickerman, 2012); however there is a general lack of published information on the method and technique and the effects of $Ca(OH)_2$ on different gases.

It is of great urgency and importance to find a solution for stack emissions for combustion processes to comply with the new standard; otherwise, almost all incinerators will have to close down and South Africa will be confronted with an immense issue of legitimately disposing of the large quantities of healthcare risk waste being produced. This may prompt occurrences where healthcare risk waste may be disposed of in residential areas, landfill sites together with municipal solid waste, and old mine dump this has occurred in the past, creating a risk to the community and the environment.

Incineration is still a well utilised technique for treating healthcare risk waste in RSA (Vehlow, 2015). The verbal confrontation over incinerators regularly includes business interests across multiple stakeholders including waste generators and incineration facilities, government departments, ecological and environmental activists and neighbourhood groups who must choose between the need for incinerators of nearby modern industry and their concerns over human well-being and environmental risks. Healthcare risk waste is a topical issue in the Republic of South Africa (RSA) as it is in numerous other countries (Vehlow, 2015).

The South African Ministry of Environmental Affairs promulgated a new regulation for General and Hazardous Waste Thermal Treatment. The progressively precise air pollution legislation requires that existing incineration facilities be adjusted to achieve the new air quality standards or face closure in the event they do not comply (Vehlow, 2015). This directive contains rigorous emission prerequisites for stack gaseous emissions and particulate matters (PM). Furthermore, to regulate and reduce any specific stack contaminants, South Africa has instituted an acceptable ambient air standard for toxic metals and toxic organics. To confirm that emissions are within stipulated regulations, incinerators are instructed to lower the acid gas emissions and to have a permanent on-line monitoring instruments for stack analysis of regulated contaminants and to send monthly reports to the authorities (NEMA Regulation, 2013).

This study was conducted to find a solution in controlling acid gas stack emissions. The study used sorbacal hydrated lime [$Ca(OH)_2$] injections to ascertain if this could reduce acid gas emissions to the recommended limits and/ or even below these limits. $Ca(OH)_2$ has not been utilised in reducing emissions produced during healthcare risk waste treatment processes; however hydrated lime injection techniques together with other emission control devices have been piloted and were found to be effective in the steel industry (Sewell and Dickerman, 2012).

1.2 Research Problem

Incineration facilities in RSA are not able to achieve the new standard prerequisite for gaseous emissions and particulate matter (Sarkar and Sarkar, 2015). Biomed has been struggling to meet the requirements since the promulgation of the new regulation. The new air pollution legislation calls for Minimum Emission Standards (MES) to be implemented to safeguard human health as part of South Africa's air quality legislation (NEMA, 2004). Since the declaration of the new legislation none of the incinerators in RSA can achieve the new prerequisites. The incineration facilities, boiler companies, steel and coal manufacturing organisations are required to reduce their stack emission levels by half. The incineration processes release toxic pollutants and harmful residues into the environment.

After the promulgation of the new standard the main problem identified was that there is no tested or tried cost effective method that can assist in reducing gaseous emissions during the incineration of waste to achieve the level required in the South

African air quality standard. Finding a cost-effective method in this study will assist in controlling emissions and minimize their creation during the combustion process. Incineration of healthcare risk waste seems like an easy solution of healthcare waste disposal. However, this technology creates more health problems by releasing toxic chemicals into the air as smoke, and into the soil and groundwater as ashes. It is imperative to find a solution to limit air pollution emissions from incinerators and reflect the maximum degree of reduction in air emissions before the regulation is amended again in 2020.

At present, Biomed is under enormous strain to conform with the new standard as their Air Emissions Licence (AEL) is soon to lapse and would only be restored provided the findings are within the recommended limits for at least six successive months (NEMA, 2013). On the emission results, the daily averages for each parameter for the previous months including the month of February 2016, have been exceeded, with HCl exceeding more than seven times the prescribed limit, PM transcending six times more than the prescribed limit, CO exceeding four times more than the prescribed limit and SO_2 reaching twice more than the prescribed limit (de Beer, 2016).

The waste material treated encompass chlorine that can produce dioxins and furans, which are carcinogenic to human beings and have been interconnected with a range of antagonistic health effects (Hatfield and Prueger, 2015). Since the promulgation of the new regulation, there is no solution available to assist with the reduction of the acid gas stack emissions to the recommended level. This may result in closure of all treatment facilities, the payment of expensive fines, or owners may be incarcerated due to non-conformance or resort to intense estimated price of redesigning and modelling their plants. Most incineration facilities, boilers and steel companies have been reporting non-compliance in terms of air quality since the implementation of the new regulation (Ragazzi *et al.,* 2013).

Combustion industries were required to extensively conform to the new regulation by 1 April 2015. However, to date, healthcare risk waste industry is considerably far from achieving the new demands (Sarkar and Sarkar, 2015). If industries are not capable of controlling the stack emissions to the minimum requirements set for April 2015, this may have disastrous effects, especially in 2020 when the recommended limits for acid gases will be reduced even more.

If all incineration facilities were to close due to air quality non-conformances, this would prompt a national catastrophe as healthcare facilities would be compelled to keep their healthcare risk waste until they find another treatment facility. Storage of healthcare risk waste at source is restricted to 30 days for anatomic waste if frozen, three days for general infectious waste and three months for sharps and needles provided the facility where waste is stored has a waste storage licence issued by Waste Management Licensing Department (AEL, 2013).

1.3 Rationale of the Research

Research was done in steel industries using hydrated lime to control gaseous emissions, however there has been a gap in healthcare risk waste researches as stated by Jiao, Zhang, Yamada, Sato & Ninomiya (2013) and Laird, Smith & Looney (2012). This industry has been struggling to control acid gas emissions since the new amended Section 21 of the NEMA: AQA 39 of 2004 came with uncompromising conditions to reduce and control gaseous pollutants. Almost all the existing treatment facilities in South Africa are not able to achieve the new compulsory demands for air quality standards (Sarkar and Sarkar, 2015). Limited research has been undertaken in steel and combustion processes (Laird *et al.,* 2012), but the topic is far from exhausted and more research is needed in the healthcare waste industry.

This research could also give a new perspective to environmental groups and communities who are against incinerators because of the emissions. Having a proven and sustainable methodology of controlling gaseous emissions could change their perspectives in viewing incinerators as the biggest polluters. The final research paper will be shared with environmental groups who may learn that emissions from incinerators could be controlled and managed using hydrated lime and that incinerators are not always bad for the environment. This research could contribute to informing policy makers of cost-effective ways of controlling gases that could be made a standard policy for all incineration facilities.

This research is important as it could prevent the closure of the existing incinerators. It has been acknowledged that there are insufficient treatment facilities in the Republic of South Africa to accommodate the growing demand of healthcare risk waste (Jiao *et al.,* 2013). The research may assist the few approved treatment facilities that are battling to achieve the new air quality standard. In the event there is no resolution, the

Department of Health, Department of Environmental Affairs and the whole healthcare risk waste industry will prospectively face a national catastrophe. As much as the government authorities are recommending the use of non-burn technologies, incinerators are still required as pharmaceutical and anatomical waste containing human blood and body parts cannot be treated with the non-burn technology (Biganzoli, Racanella, Rigamonti, Marras & Grosso, 2015).

The purpose of this research was to assess a cost-effective practice of controlling acid gas emissions that would not be difficult to implement with no significant changes to existing plants. Hydrated lime injections were utilised to establish the capabilities in controlling acid gas stack emissions at maximum temperatures. This study will not only be of use to the healthcare risk waste industry but also to the steel and iron industry, boilers, coal firing and other industries running combustion processes, which are also trying to minimise their acid gas emissions to the recommended limits.

There is room for research to help the environmental industry, treatment facilities, boilers and steel industries to reduce their stack emissions and conform to the standards. In many occurrences there is no technique for old plants to achieve compliance. Moreover, there are constraints regarding proficiency in South Africa to stimulate the execution of new technologies in some cases. Direct costs can be minimised, managed and timelines to achieve such modifications may not be met.

1.4 Aim

The main aim of the study was to evaluate the control of stack emissions using hydrated lime injections during incineration of healthcare risk waste. The research investigated the effective $Ca(OH)_2$ dosage rate and the degree of reactivity of $Ca(OH)_2$ with different gases at different temperatures.

1.5 Research Objectives

The specific objectives of the study were to:

i) Investigate the optimum dosage rate for $Ca(OH)_2$ required to reduce acid gas emissions.
ii) Evaluate the degree of reactivity of $Ca(OH)_2$ with different gases at different temperatures.
iii) Determine the reduction in the amount of acid gas emissions due to $Ca(OH)_2$ injections.
iv) Investigate the impact and relationship between $Ca(OH)_2$ injections and particulate matter.
v) Evaluate the effectiveness of $Ca(OH)_2$ in reducing acid gas emissions in the incineration of healthcare risk waste.

1.6 Hypotheses

i) In line with the objective aimed to investigate the optimum dosage rate for $Ca(OH)_2$ required to reduce acid gas emissions, it was hypothesised that:

Hypothesis 0 (null hypothesis): There is no relationship between acid gas emissions and lime dosage rate.

Alternative hypothesis: There is a relationship between acid gas emissions and lime dosage rate.

ii) In line with the objectives aimed to evaluate the effectiveness of $Ca(OH)_2$ in reducing acid gas emissions and the relationship between $Ca(OH)_2$ injections and particulate matter, it was hypothesised that:

Hypothesis 1 (null hypothesis): Hydrated lime injections have no effect in the amount of acid gas emissions and particulate matter.

Alternative hypothesis: Hydrated lime injections have an effect in the amount acid gas emissions and particulate matter.

1.7 Study Area

Biomed Disposal Services is a treatment facility situated in Dunswart Industrial (latitude $26^0$12'34 51" and longitude $28^0$17'32 41") in Ekurhuleni. Ekurhuleni Metropolitan area is known as Highveld priority area in respect of air quality management, meaning that it is a demarcated area inside which the ambient air quality standards are being compromised and may cause health and environmental impacts (NEMA, 2004). The location is positioned in a traditional industrial and commercial zone with a residential area, Lakefield, approximately one kilometre away to the north. The residential area of Actonville is to the east and south of the site, with the closest housing approximately 500 metres away (Figure 1.1). The location does not have surface water, crucial biodiversity portions, protected areas or buffer areas (Saner, 2012).

Biomed incinerates roughly 300 tons of healthcare risk waste every month, all originating from private and public healthcare facilities around the country. The types of waste incinerated on site include anatomical waste, sharps and needles, any solid or liquid waste that is created through the diagnosis or treatment of humans or animals in research facilities, cultures, tissues, dressings, swabs, and waste holding pathogens from isolation wards, genotoxic drugs and chemicals used, for instance, in cancer therapy and general infectious waste. At this incineration facility, the combustion of healthcare waste happens in two phases. In the first phase, waste is sustained into the primary chamber where gases are produced during combustion (Figure 1.2). The second phase takes place in the secondary chamber where high temperature is applied up to 1200°C to combust gases generated in the primary chamber.

Biomed is operating under two licences: Atmospheric Emission Licence (AEL) authorised by Ekurhuleni Metropolitan Municipality and Waste Management Licence authorised by the Department of Environmental Affairs. Biomed is battling to reach the new stringent pre-requisites for emission standard that incineration facilities require to conform with to work as a treatment facility. If Biomed cannot conform with the new emission standard demands, it would be compelled to close down the facility, a catastrophic emergency in terms of healthcare risk waste disposal.

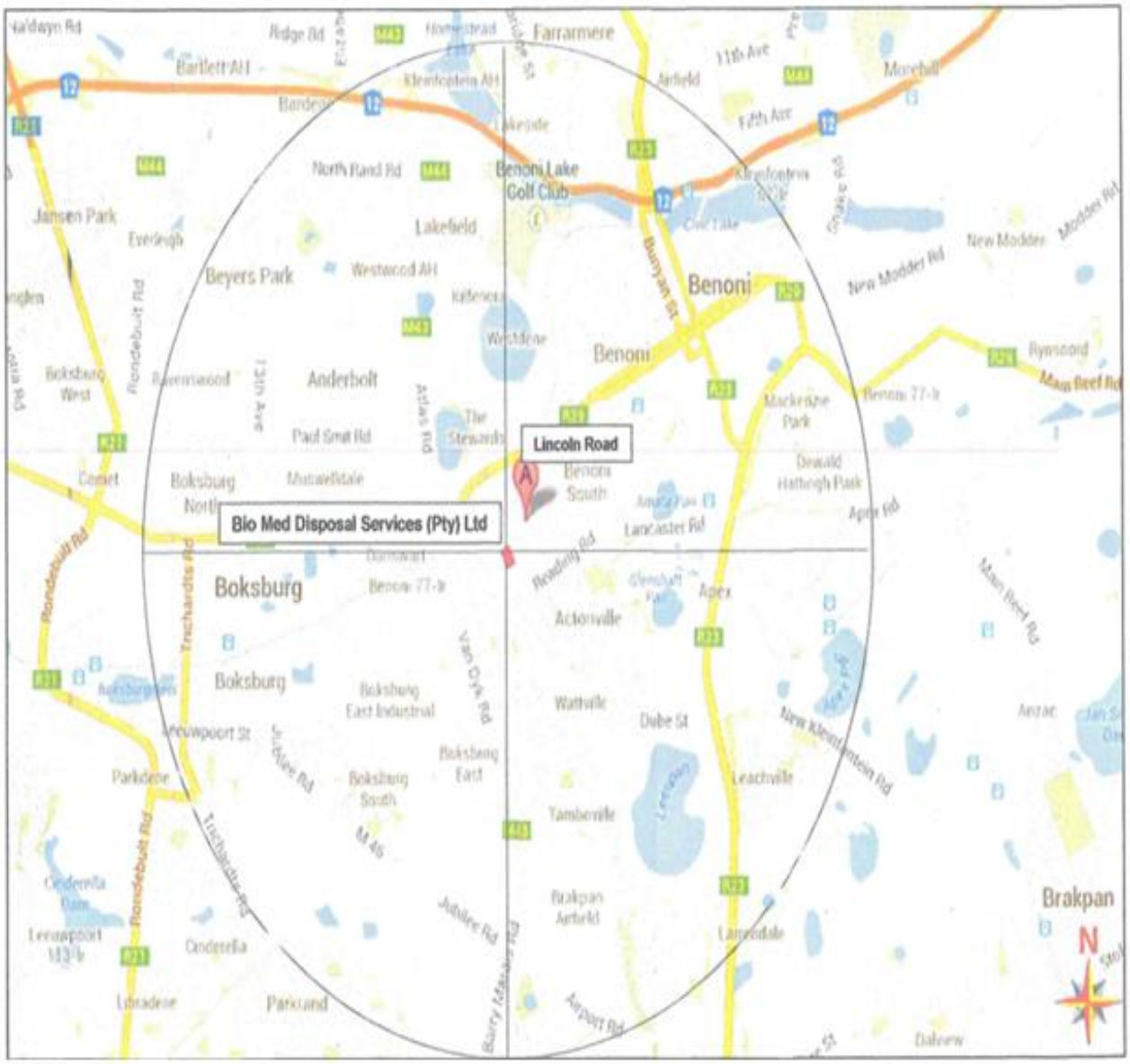


Figure 1.1: Map showing surrounding areas of the site within 5km (Source: Saner, 2012)

Scale 1:1000

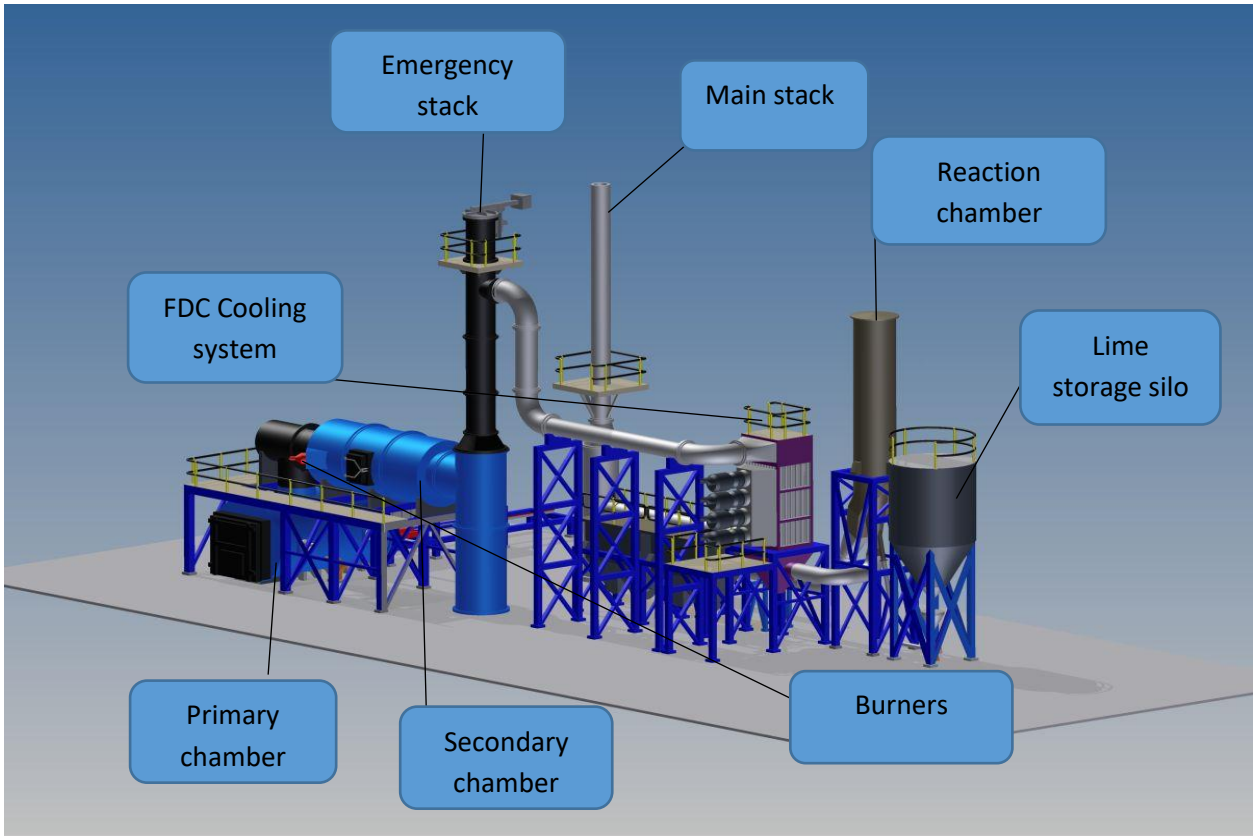


Figure 1.2: RD 500 Healthcare risk waste incineration facility (Howden, 2013)

1.8 Outline of the Dissertation

Chapter 1: Introduction provides a background to the incineration of healthcare risk waste and gaseous emissions, problems associated with incinerator emissions, contribution of acid gas emissions towards climate change, the South Africa's commitment to reduce emissions. It also provides the rationale for the study, research problem, the aim and objectives and a delineation of the study area.

Chapter 2: Literature review covers the following:

- Formation of gaseous emissions
- The impact of gaseous emissions on the environment
- The impact of using dry sorbents sodium
- The effects of hydrated lime on gaseous emissions

- The effectiveness of hydrated lime in neutralising gaseous emissions, effect of hydrated lime on mercury
- The impact of hydrated lime and temperature reliance in sorbent injections
- Dry sorbent injection testing using hydrated lime
- Air pollution control technique in modern incinerators
- Legal framework for gaseous emissions from waste combustion
- Low temperature dry sorbent
- High temperature dry sorbent injection
- Dry sorbent injections in healthcare waste incineration plants.

Chapter 3: Research Methodology outlines a brief overview of the area, the research methodology used during the study, research design, sampling methods, data collection, data analysis and limitation of the study.

Chapter 4: Research Results and Discussion presents the results of the study in the form of descriptive statistics and a discussion.

Chapter 5: Conclusion provides a conclusion to the study and offers some recommendations for future studies.

Chapter 6: Recommendations

Chapter 2: Literature Review

This chapter presents various theories on the impacts of sorbacal $Ca(OH)_2$ injections used to reduce gaseous emissions in different industries. Hydrated lime has had some positive results when used in other combustion processes such as (Jiao, Cheng, Zhang, Yamada, Sato & Ninomiya, 2011; Laird, Smith & Looney, 2012 and Dowling, O'Dwyer & Adley, 2015).

2.1 Formation of Gaseous Environmental Emissions

Gaseous emissions are classified into two main categories known as primary and secondary pollutants. Primary pollutants are gases that are discharged straight from the stack known as point sources. Some of the known primary pollutants incorporate sulphur dioxide emissions from combustion procedures, for example, incinerators, furnaces, boilers, and natural compound emissions from surface coating facilities (Borlace, Cai, Lengaigne, Van Rensch, Collins, Vecchi, Timmermann, Santoso, McPhaden, Wu & England, 2014).

Secondary pollutants are gases and vapour form components that are created based on reactions between primary pollutants in the environment or between primary pollutants and naturally transpiring compounds in the environment (Borlace *et al.,* 2014). The most well perceived classification of secondary contaminants incorporates ozone and other photochemical oxidants generated due to sunlight-initiated reactions of nitrogen oxides, organic compounds, and carbon monoxide. A synopsis of the fundamental classifications of gaseous emissions is given as follows (Jenner, 2013):

a) Primary gaseous contaminants

- Sulphur dioxide (SO_2) and sulphuric acid vapour
- Nitrogen oxide (NO_x) and nitrogen dioxide (NO_2)
- Carbon monoxide (CO) and partially oxidised organic compounds
- Volatile organic compounds (VOC) and other organic compounds
- Hydrogen chloride (HCl)
- Hydrogen fluoride (HF)
- Hydrogen sulphide (H_2S) and other total reduced sulphur compounds
- Ammonia (NH_3)

b) Secondary gaseous contaminants

- Nitrogen dioxide (NO_2)
- Ozone (O_3) and other photochemical oxidants
- Sulphuric acid (H_2SO_4)

There is no clear distinction between primary and secondary gaseous emissions. For instance, nitrogen dioxide and sulphuric acid are in both classifications. All primary gaseous pollutants can interact in atmospheric reactions to develop secondary reaction compounds (Jenner, 2013). Gases generated during the treatment of healthcare risk waste are mainly referred to as primary gaseous contaminants because of their known source (Vehlow, 2015). During the treatment of healthcare risk waste SO_2 is generated fundamentally during the ignition of a sulphur containing fuel, or sulphur encompassing mechanical waste gases. When discharged on the environment, sulphur dioxide responds gradually on grounds of photochemical initiated reactions and interacts with cloud and fog droplets (Vehlow, 2015).

Climate and Development Knowledge Network (2012) defined Nitrogen oxides (NO_x) as a combination of nitric oxide (NO) and nitrogen dioxide (NO_2). During the combustion process, NO prevails because of dynamic constraints in the oxidation of NO to NO_2. Nitrogen oxides are generated during incineration of waste mainly from two sources: by the fixation of molecular nitrogen in air and by the oxidation of chemically bound nitrogen in the wastes (Climate and Development Knowledge Network, 2012).

Hydrogen chloride is produced during the incineration of healthcare risk waste from organic and part of inorganic chlorine material (Antonioni, Guglielmi, Cozzani, Stramigioli & Corrente, 2014). The primary sources of chlorine are plastics such as PVC, salty food waste and other inorganic chlorides. Combustion of healthcare risk waste generates pollutants of approximately 2.9 g HCl/ kg (Antonioni *et al.,* 2014). In the process of combustion of healthcare risk waste, HCl reacts with components of incomplete combustion to create chlorinated phenols and benzenes, whose formation predate the generation of dioxins and furans (Guglielmi, Antonioni, Stramigioli & Cozzani, 2014. Guglielmi *et al.* (2014) stated that these predecessor reactions take place below 850°C, but most efficiently around 750°C. Chlorine and fluorine may be found in healthcare risk waste in large concentrations. Under heat conditions, chlorine and fluorine are generally transformed into acid hydrogen halides, HCl and HF may react to generate metal chlorides (Guglielmi *et al.,* 2014).

Particulate matters are particularly generated in the incineration process during the poking of waste, utilisation of hydrated lime injections, removal of ash, cleaning and removal of refractories in the primary and secondary chambers (Buonanno, Scungio, Stabile & Titler, 2012). These particulates are generally classified based on their diameters, for example $PM_{2.5}$ with a diameter smaller than 2.5µm and PM_{10} with a diameter smaller than 10µm. PM_{10} which is emitted by the incinerators may remain in the atmosphere for long intervals, moving long distances and is able to penetrate deep into the respiratory tract (United Nations Framework Convention on Climate Change, 2011).

Hydrogen chloride and Hydrogen fluoride are acid gases that are generated from mechanical industrial procedures such as waste incineration processes, non-renewable fired boilers, chemical reactors or ore roasting activities (Van Caneghem, De Greef, Block & Vandecasteele, 2016). They can also be released in air contamination control systems oxidising chlorine or fluorine containing organic compounds. Van Caneghem *et al.* (2016) stated that the concentrations of HCl and HF generated during waste incineration treatment activities and fossil fuel combustion are instantly connected to the chloride and fluoride concentration of the waste or fuel being treated. Buonanno *et al.* (2012) said that most of the chloride and fluoride atoms in the fuel or waste being treated transform to HCl or HF as long as adequate hydrogen atoms are available from hydrocarbons or water vapour in the gas stream. Often, less chloride or fluoride ions remain in the ash by-products.

2.2 Importance of Controlling the Emissions in South Africa

South Africa's gaseous emissions are among the highest in the world and its absolute carbon dioxide emissions rank among the top twenty countries, with emissions per capita in the region of 10 metric tons per annum (Mathieu, Finkernagel, Murawska, Scharfe, Jarek & Brehm, 2012). The 2011 National Climate Change White Paper described this challenge as, the energy intensity of the South African economy, largely due to the significance of mining, steel industry, combustion processes and minerals processing in the economy. Our combustion plants have resulted in emissions profile that differs substantially from that of other developing countries at a similar stage of development as measured by the Human Development Index (National Climate Change White Paper, 2011).

Since coal in combustion processes is the most emissions-intensive energy carrier, South Africa's economy is very emissions-intensive. Furthermore, emissions from land-use change primarily deforestation which contribute a significantly smaller share to our emission profile than for many other developing countries. In 2000, the average energy use for emissions in developing countries constituted 49% of total emissions, whereas South Africa's energy use emissions constituted just under 80% of total emissions (United Nations Framework Convention on Climate Change, 2011). Even in some fast-developing countries with a similar reliance on coal for energy, energy use emissions are lower than South Africa (COP 21, 2015).

South Africa has national and international legal obligations to reduce its emissions (Climate and Development Knowledge Network, 2012). The Bill of Rights section of the South African Constitution includes an environment clause, which states that everyone has the right on the following:

a. To an environment that is not harmful to their health or well-being; and
b. To have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that:

i. Prevent pollution and ecological degradation;
ii. Promote conservation; and
iii. Secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development (Constitution of the Republic of South Africa, 1996).

South Africa is party to a number of multinational environmental agreements. These include the United Nations Framework Convention on Climate Change (UNFCCC), which South Africa ratified in 1997; the Kyoto Protocol, which South Africa ratified in 2002; and the Paris Agreement on Climate Change, ratified by South Africa in 2016. In the 2009 Copenhagen Climate Change Conference, South Africa committed to reducing its gaseous emissions by 34% below its current levels by 2020 and 42% below current levels by 2025, with emissions peaking in 2020 - 2025, stabilizing in 2025 - 2035 and declining in absolute terms from around 2035 (Sarkar and Sarkar, 2016).

As part of its plan to implement the environment clause of the Constitution and its obligations under international law, South Africa enacted the National Environmental Management: Air Quality Act in 2004 (NEMA Regulation, 2013). The Act delegates a

great deal of power to the executive branch to, among other things, put in place national policy and a regulatory framework for pollution prevention and the enhancement of air quality (NEMA Regulation, 2013).

2.3 Environmental Challenges in South Africa

Since the implementation of the National Environmental Management Air Quality Act, in November 2013, the importance of emissions control in South Africa has been increasing (Goitom, 2018). Moja and Mnisi (2013) stated that in the past, industries focused mainly on protecting their workforce and machinery from hazardous substances. However, today, companies must not only protect the inside of a plant but also control what is released into the atmosphere around the plant (Moja and Mnisi, 2013). The emissions generated from different industrial processes need to be collected at the source, which ensures a healthy working environment and reduces or even eliminates particulate emissions. In addition, to optimize particulate collection efficiency, the way in which dust and fumes are collected needs to be managed with energy efficiency (Moja and Mnisi, 2013).

Air pollution is a major concern in areas of heavy industrial development such as the Vaal Triangle Airshed Priority Area, South Durban Industrial Basin (SDIB) and the Highveld Priority Area (HPA). Poor past land use planning in South Africa has resulted in the positioning of heavy industrial developments in proximity to heavily populated residential areas (McCarthy, 2011). The negative environmental effects of air pollution resulting from industrial operations are felt directly during the active phase. However, in some cases, these negative environmental effects may be experienced long after industrial operations have ceased. This is evident in Gauteng where mine residue areas resulting from intensive mining activities which were undertaken in the Witwatersrand, have become a serious source of wind-blown dust. Compounding the problem is the proximity of human settlements right up to the foot of the mine tailings storage facilities (McCarthy, 2011).

According to Goitom (2018) South Africa may soon impose a carbon tax on emissions. On December 14, 2017, the country's National Treasury issued the second draft bill on carbon tax for public comment and introduction before Parliament. Based on the "polluter pays" principle, if enacted in its current form, the proposal would introduce a carbon tax in phases in which the rate would be set at R120 per metric ton of carbon

dioxide above the tax-free allowances. The rate would increase every year parallel to consumer price inflation plus 2% up to December 31, 2022. After that, the rate would be determined by the amount of the consumer price inflation for the preceding tax year (Goitom, 2018).

According to DEA (2007) the most common air pollutants in the country are shown in Table 2.1. The priority pollutants are a good indicator of air quality in general.

Table 2. 1: Pollutants of concern in South Africa (Source: DEA, 2007)

Current criteria pollutants	**Possible future pollutants**	
	National pollutants	**Local pollutants**
Sulphur dioxide	Mercury	Chrome
Nitrogen dioxide	Particulate matter ($PM_{2.5}$)	Fluoride (particulate and gas)
Ozone	Dioxins	Manganese (Mn)
Carbon monoxide	Furans	
Lead (Pb)	POPs	
Particulate Matter (PM_{10}) Benzene	Other VOCs	
	Pollutants controlled by international conventions ratified by South Africa	

2.4 Health Risks Associated with Poor Air Quality

Air pollution can cause adverse health impacts (McCarthy, 2011). Pollution from the burning of domestic fuel, incineration facilities, boilers and furnaces have been described as the largest contributor to the negative health impacts of air pollution (Alburto, Ziolkovska, Hooper, Elliott, Cappuccio & Meerpohl, 2013). According to Naidoo (2017) who conducted a study in South Durban aimed to assess the influences of industrial and vehicular emissions on respiratory health, to survey the range of ambient exposures and to determine the health risk these pose for the community.

Naidoo (2017) concluded that the lifetime cancer risks are as a result of inhaling harmful pollutants. Individual lifetime risk is defined as the increased lifetime risk of cancer for an individual exposed to the maximum predicted long-term concentration (Naidoo, 2017). The largest risks were posed by VOC's (benzene) and semi-volatile compounds (dioxins, furans and naphthalene).

Naidoo (2017) also indicated that for children attending primary school in South Durban, compared to the northern suburbs, had an increased risk for persistent asthma and for marked airway hyperactivity. Higher outdoor concentrations of nitrogen dioxide, nitrogen oxides, PM10, and sulphur dioxide were strongly and significantly associated with poorer lung function notably among children with persistent asthma and children with certain genes on days following exposure. For adults, living in communities in the south, as compared to the north, was significantly associated with hay fever, and somewhat associated with chronic bronchitis, wheezing with shortness of breath, and hypertension (Naidoo, 2017).

2.5 What has South Africa Done to Respond to Air Quality Problems?

Various air quality management instruments have been developed over the years and include environmental legislation, emissions inventories, dispersion modelling and concentration inventories (Oosthuizen, John & Somerset, 2010). South Africa has responded to its air pollution challenges in various ways, which include legislative reform, revision of ambient air quality limits, proactive planning by local authorities and sector specific controls as indicated below (Oosthuizen *et al.,* 2010):

- The promulgation of the NEM: AQA - Key elements of this are the establishment of a clear institutional and planning framework for air quality management;
- The development of a South African Air Quality Information System (SAAQIS) to ensure the availability of credible and readily available air quality data. This data is in turn used to ensure that appropriate measures to improve air quality are taken;
- The development and maintenance of an effective governance framework for air quality management, National Framework for Air Quality Management in South Africa, as provided for in the NEM: AQA, to ensure that current and future

impacts of atmospheric emissions are avoided, minimized, mitigated or managed;

- Declaration of priority areas, as provided for in the NEM: AQA and ensuring that there are significant improvements in air quality in the declared priority areas and compliance with the ambient standards;
- Development of national, provincial, municipal and priority area Air Quality Management Plans (AQMPs) in fulfilment of the requirements of the NEM: AQA in areas with poor or potentially poor air quality;
- Improvement of indoor and ambient air quality in dense, low-income urban settlements through ambient monitoring, Basa njengo Magogo (BnM), housing guidelines, energy carrier options and the strategy for addressing air pollution in dense, low income settlements, especially given the fact that it is proposed that by 2020 air quality in all low-income settlements should be in compliance with National Ambient Air Quality Standards (NAAQS).

It is evident that South Africa has the great policies and instruments to report and manage air quality problems. What is still lacking is a technology to reduce the emissions within an acceptable standard (Oosthuizen *et al.,* 2010).

2.6 The Impact of Gaseous Emissions on the Environment

Gaseous emissions are understood to be a big contributor of atmospheric pollution leading to acid smog formation and acid rain. These pollutants have been confirmed to be unsafe prompting asthma, respiratory diseases and are related to growing mortality (Mathieu *et al.,* 2012). Numerous countries and the World Bank have established or are sanctioning increasingly stringent regulations restricting the release of gaseous emissions into the environment (Mathieu *et al.,* 2012).

The Kyoto Protocol was formulated to enforce restrictions on gaseous emissions and greenhouse gases to handle the concerns over increasing environmental impacts and to reduce global warming (Antonioni, Sarno, Guglielmi, Morra & Cozzani, 2011). Gaseous pollutants are the cause of various adverse environmental impacts such as photochemical smog, acid rain, extinction of forests, and lower atmospheric visibility. Greenhouse gas emissions from combustion of fossil fuels are strongly contributing to global warming and climate change. Specific air contaminants, encompassing black

carbon, not only cause global warming, but are also associated with immediate impacts on regional climates (Antonioni, Guglielmi, Stramigioli & Cozzani, 2012).

2.6.1 World Environment Day 2019 Highlights SA Deaths from Air Pollution

On the 5th of June each year, the United Nations hosts World Environment Day, which is used to bring global awareness to severe environmental issues that require urgent political action. This year's (2019) World Environment Day is especially significant for South Africa where air pollution from coal-fired power stations kills more than 2 200 people every year (Centre of Environmental Rights, 2019). The theme for the 2019 United Nation's annual World Environmental Day is "Beat Air Pollution" and aims to draw attention to the silent killer around us.

According to recent data from the World Health Organization, more than 7 million people die from air pollution, globally, every year. This includes more than 1.7 million child deaths every year, worldwide. A 2017 report by United Kingdom based air quality and health expert, Dr. Mike Holland, found that air pollution from coal-fired power stations kills more than 2,200 South Africans every year, and causes thousands of cases of bronchitis and asthma in adults and children annually (Centre of Environmental Rights, 2019). The Director of environmental justice group groundWork said this costs the country more than R34 billion annually, through hospital admissions and lost working days (Centre of Environmental Rights, 2019).

The study (WHO, 2017) made the following findings:

- 2 239 deaths per year: 157 from lung cancer; 1 110 from ischaemic heart disease; 73 from chronic obstructive pulmonary disease; 719 from strokes; and 180 from lower respiratory infection
- 2 781 cases of chronic bronchitis per year in adults
- 9 533 cases of bronchitis per year in children aged 6 to 12
- 2 379 hospital admissions per year
- 3 972 902 days of restricted activity per year
- 94 680 days of asthma symptoms per year in children aged 5 to 19

- 996 628 lost working days per year

WHO (2017) shows how pollution costs South Africa and people living here an enormous amount in medical costs, lost working days, and lost development opportunities. The worst air pollution is caused by emissions from coal-fired power stations and combustion operations. Civil society and community organizations like groundWork, Earthlife Africa, Centre for Environmental Rights (together the Life After Coal campaign), Federation for a Sustainable Environment, South Durban Community Environmental Alliance, and the Vaal Environmental Justice Alliance, have battled with big polluters and authorities for decades. These Civil societies are arguing that the poor air quality in areas like the Mpumalanga Highveld, the Vaal Triangle, Limpopo Waterberg and South Durban constitute violations of the Constitutional right to an environment not harmful to health or wellbeing (Centre of Environmental Rights, 2019).

In May 2019 the Department of Environmental Affairs was forced to set aside standards that would allow all coal-fired boilers to double the amount of the harmful pollutant sulphur dioxide (SO_2) they are allowed to emit into the air from April 2020. Department of Environmental Affairs concedes, in its own annual State of the Air reports from 2010 to date, that air pollution is a challenge and that air quality does not meet even South Africa's weak ambient air quality standards, but has, to date, denied that this constitutes a violation of human rights (Centre of Environmental Rights, 2019).

2.6.2 Acid Deposition

Acidic deposition occurs when emissions from the combustion of fossil fuels and other industrial processes undergo chemical reactions in the atmosphere to form acidic compounds and are deposited as wet deposition and dry deposition. The main chemical precursors leading to acidic conditions are atmospheric concentrations of sulphur dioxide and nitrogen oxides (ARPA, 2011).

In South Africa, the industrial Highveld plateau is considered as a significant source of pollutants associated with acid deposition and accounts for approximately 90% of South Africa's scheduled emissions of industrial dust, sulphur dioxide and nitrogen oxides (McCarthy, 2011). A major study on acid deposition over South Africa indicated that concentration distributions for acidic gases sulphur dioxide and nitrogen dioxide show prevailing high concentrations over the industrial Highveld (McCarthy, 2011).

The main findings indicated that the levels of acid deposition measured in the study do not exceed, and are not likely to exceed, critical levels and thus the challenge of acid rain over South Africa is not as serious an issue as previously thought.

Acid rain affects plants and animals and produces complex changes in normal soil chemistry. It also causes staining and chemical corrosion of buildings and monuments resulting in high economic costs.

2.6.3 Stratospheric Ozone Depletion

The ozone layer is an atmospheric layer of naturally occurring ozone gas that is located approximately 15 to 30 km above the earth and serves as a shield from the harmful ultraviolet radiation emitted by the sun (Kondache, Koffi, Kayode, Awokola & Adebola, 2018). There is widespread concern that the ozone layer is deteriorating due to the release of gaseous emissions. Such deterioration allows large amounts of ultraviolet rays to reach earth, which can cause among others, adverse health impacts, skin cancer and cataracts in humans and harm to plants and animals (Kirk-Davidoff *et al.,* 1999). Hydrochlorofluorocarbons (HCFCs) dominate consumption at approximately 25,759 tons (81.4 per cent) of total ozone depleting substances (ODS) consumed during the period 2004 to 2009 in South Africa (DEA 2013).

There is a range of possible health impacts of stratospheric ozone depletion. Many epidemiological studies have implicated solar ultraviolet radiation as a cause of skin cancer (melanoma and other types). Assessments by the EPA (2012) projected significant increases in skin cancer incidence due to stratospheric ozone depletion. The assessment anticipated that for at least the first half of the twenty first century (and subject to changes in individual behaviors) additional solar ultraviolet radiation exposure would augment the severity of sunburn and incidence of skin cancer. High intensity ultraviolet radiation also damages the eye's outer tissues causing 'snow blindness', the ocular equivalent of sunburn (EPA 2012).

Norval *et al.* (2011) shows that high ambient solar ultraviolet radiation, particularly UVB exposure, occurs in countries such as South Africa, Australia and New Zealand. South Africa has very high levels of solar radiation, over twice that of Europe and 1.5 times higher than in the United States (Norval *et al.,* 2011).

2.7 The Reactivity of Hydrated Lime with Gaseous Emissions

There are two fundamental categories of lime manufactured around the world, quicklime and hydrated lime. Quicklime is produced during the calcination of limestone. Hydrated lime is formed from subsequent hydration of quicklime where necessary (Dowling *et al.,* 2015). Lime has been unconventionally rediscovered to be a more environmentally sustainable commodity used in the execution of new cleaner systems, reduction of acid mine drainage to major uses in water source treatment. Additional research has been conducted to assess new possibilities for lime as an antimicrobial compound and environmentally friendly biocide (Dowling *et al.,* 2015).

Major uses of lime have been confirmed in numerous areas of pollution prevention and reduction; these incorporate treatments of drinking water and wastewater, reduction of gaseous emissions and treatment of hazardous waste (Antonioni, Dal Pozzo, Guglielmi, Tugnoli & Cozzani, 2016). Hydrated lime is considered a feasible sorbent in neutralising gaseous emissions and is mentioned in the Intergovernmental Panel on Climate Change (IPCC) Special Report (Antonioni *et al.,* 2012). It is generally utilised in steel and coal combustion processes to capture gaseous emissions. To date, nothing has been used in South Africa to control acid gas emissions generated during the treatment of healthcare risk waste or any combustion processes. Operational expenses for the pollutants capturing systems are a critical cost for incineration facilities (Linnenluecke, Griffiths & Winn, 2013).

Various scrubbing techniques have been used in boiler and steel industry for many years because of their effectiveness but the cheaper and easier technique to implement is usually dry sorbent injection (DSI) systems. In DSI systems, a dry powdered alkaline material is introduced into the flue gas stream to reduce the acidic species and the formation of solid salts. The remaining residue of alkaline material is collected by a downstream particulate control device (Antonioni, Guglielmi, Cozzani, Stramigioli & Corrente, 2014). Dry $Ca(OH)_2$, a calcium based alkaline sorbent, is often used in dry scrubbing, mostly due to its low cost and accessibility (Antonioni *et al.,* 2014).

In DSI systems that use hydrated lime, the reactivity with any specific acid gas is affected by various factors. There is competition in flue gas for hydrated lime between CO_2, SO_2, sulphur trioxide (SO_3), HCl and HF, but the degree that hydrated lime is responsive to any of these flue gases rests on the temperature at which hydrated lime

and the specific acid gas first come into contact (Laird *et al.,* 2012). However, keeping a consistent incinerator temperature is not easy because of unstable calorific values and moisture contents found in healthcare risk waste (Astrup, Riber & Pedersen, 2011).

According to Lard *et al.* (2012), the reactivity of $Ca(OH)_2$ with SO_2 takes preference at around 1000°F (538°C) but is heavily influenced by physical attributes of hydrated lime like surface area and the feeding rates. Lard *et al.* (2012) concluded that the reactivity increased between calcium and SO_2 as flue gas cools and approaches saturation for water vapour.

Different acid gases compete for hydrated lime, which is strongly influenced by the temperature at which hydrated lime comes into contact with gases. The particulate emissions are found to be correlated with the gaseous emissions as the products of incineration process (Bologa, Paur, Seifert, Woletz & Ulbricht, 2012). Figure 2.1 illustrates, in general, the reactivity of hydrated lime with other prominent acid gases over a temperature range beginning around 250°F (121ºC) to around 850°F (454°C) (Laird *et al.*, 2012). It is notable that if both SO_2 and HCl need to be captured through DSI, hydrated lime would need to be injected at various flue gas temperature intervals depending on the removal rate desired for acid gases.

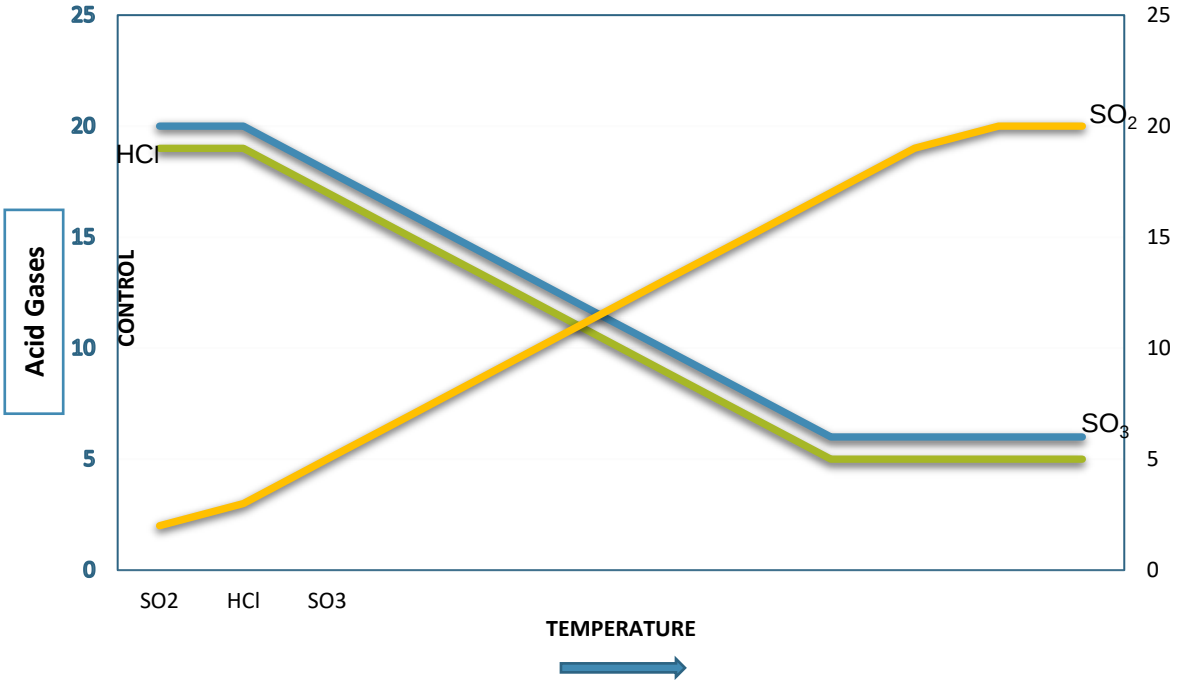


Figure 2.1: Impact of competing acid gases for hydrated lime as a function of temperature (Source: Laird *et al.,* 2012)

2.8 The Impact of Using Dry Sorbents Sodium

From various research, it is evident that $Ca(OH)_2$ can be utilised to capture and reduce acid gas emissions (such as Quicker, Rotheut, Noël, Schulten & Athmann, 2014; Laird, Smith & Looney, 2012 and Dowling, O'Dwyer & Adley, 2015). However, numerous of those researches conducted were not certainly done at incineration facilities but at steel manufacturing companies, boilers or coal combustion plants. What is also in question from these studies is the degree of $Ca(OH)_2$ reactivity with various gases at different temperature intervals (Jiao *et al.,* 2011).

The current study is similar to the study done by Laird *et al*. (2012). Laird *et al*. (2012) made use of $Ca(OH)_2$ injections at temperatures varying from 121°C to 454°C because they concluded that the unsurpassed reactivity occurs at minimum temperatures. The current study however contrasts with Laird *et al*. (2012) in that $Ca(OH)_2$ was utilised as a sodium sorbent of choice injected at high flue gas temperatures. In the current study, the temperatures were maintained between 850°C on the primary chamber and up to 1200°C on the secondary chamber followed by fabric filtration for particulate matters (PM) control. The reactivity of $Ca(OH)_2$ with various gases was then measured and compared to the new legislation requirements.

The use of dry sorbent injections has become prominent as an essential SO_2, HCl, and mercury reduction technique because of its low capital cost; minimum installation footprint; easy methods to implement; and adaptability to fuel changes (Kong and Davison, 2010). In a dry sorbent injection system, trona or sodium bicarbonate is introduced directly into hot flue gas. After injection, the sorbent is calcined into porous sodium carbonate that responds with SO_2, HCl and SO_3 (Biganzoli, Racanella, Marras & Rigamonti, 2015).

In a study conducted by Biganzoli *et al.* (2015), in coal fired plants, sodium bicarbonate was introduced directly into hot flue gas. After injection, the sorbent was calcined into porous sodium carbonate that responded with acid gases. This method was successful in reaching high reduction rates of >99% for HCl and >90% for SO_2, and has been administered in various waste incineration facilities in Europe and coal-fired power plants in the USA (Bichisecchi, 2014).

Dry sorbent injections have also been used in older and smaller (< 300 Megawatt electric) coal-fired power plants including fluidised bed and pulverised coal boilers

(Laird *et al.,* 2012). These facilities had little space for flue gas desulphurisation equipment and a limited or uncertain life span to extend operations and meet new emission requirements for HCl, PM, mercury (Hg) and possibly dioxin and furans. They were then required to employ DSI followed by either an electrostatic precipitators (ESP) or a fabric filter for PM control (Laird *et al.,* 2012).

2.9 Effectiveness of Hydrated Lime in Neutralising Gaseous Emissions

According to Sarkar and Sarkar (2015), one considerable disadvantage of dry sorbent injections is that the method can only capture between 40% to 80% SO_2 when utilising limestone and hydrated lime at Ca/S molar ratios of 2.0 moles. The limestone with involuntary oxidation method can capture more than 90% SO_2 utilising 1.05 to 1.1 moles CaO/mole. This contradicts what other researchers have stated regarding $Ca(OH)_2$, that it is a responsive agent to countervail acid gases by up to 90% (Laird *et al*., 2012; Biganzoli *et al*., 2015; Dowling *et al*., 2015).

Gupta, Ibrahim & Shoaibi (2016) are in agreement with (Dal Pozzo, Antonioni, Guglielmi, Stramigioli & Cozzani (2016) who stated that a dry sorbent is the cheapest technique used in capturing gaseous emissions. Gupta *et al.* (2016) concluded that the least complex sorbent injection innovation is the furnace sorbent injections. In this procedure a dry sorbent is introduced into the upper part of the furnace to capture all gaseous emissions present in the flue gas system. The powdery form sorbent is disseminated rapidly and equitably the entire cross-area in the higher part of the furnace, in an area where the temperature is in the region of 1023K (Kelvin) (750°C) to 1523K (1250°C). The flue gas passes through the transmission chute, where the temperature stays between 750°C and 1250°C, and the sorbent reacts with SO_2 and O_2 to form $CaSO_4$, which is later collected in a fabric filtration system or ESP successively with unutilised sorbent and fly ash (Gupta *et al.,* 2016).

However, Guglielmi, Antonioni, Stramigioli & Cozzani (2014) was not in agreement with Gupta *et al.* (2016) and Dal Pozzo *et al.* (2016). Guglielmi *et al.* (2014) reported that except for CO and Total Organic Compound (TOC) which can only be affected by essential reactions inside the furnace (blending, temperature, and resident time), all emissions can be captured with different techniques and advancements. For example,

NO_x emission can be treated inside the furnace (staged combustion) by specific non-catalytic reduction (SNCR) and by means of selective catalytic reduction. The process of non-catalytic reduction involves ammonia injections in to the fire bed of the boiler at an area where the temperature is between 760°C and 1090°C to react with the nitrogen oxides produced in the combustion process (Guglielmi *et al.,* 2014).

Guglielmi *et al.* (2014) also concluded that HCl and HF can be captured in scrubbers or by chemisorption involving a chemical reaction between the surface and the gases. Kassman (2011), on the other hand, stated that injection of ammonium sulphate significantly lowered the level of gaseous emissions as compared to using hydrated lime injections and there almost no chlorine was found in the deposits.

With regard to SO_2, Guglielmi *et al.* (2014) was in agreement with Gupta *et al.* (2016) and Dal Pozzo *et al.* (2016) who indicated that SO_2 can, in fluidised-bed combustors, be reduced by means of injecting limestone into the combustion chamber, but it can likewise be changed over in wet, semi-dry or dry scrubbing methods. Similarly, dioxins and furans may be captured under complete combustion scenarios or adsorption or combustion procedures. Moreover, Hg can be reduced either in scrubbing or in adsorption methods (Guglielmi *et al.*, 2014).

Furthermore, Guglielmi *et al.* (2014) proposed that, due to the need for adapting to substantial contrast in the firing attributes of solid waste, the facilities must be operated with objectively high amounts of oxygen in the system and this reduces the energy efficiency. This, however, contradicts the NEMA: AQA Government Gazette 37054 which recommends that the level of reference for O_2 be limited to 10% during combustion of healthcare risk waste.

Different authors do not agree on the exact removal efficiency for different gases. More ever, Gupta *et al.* (2016) stated that in the dry scrubbing process, flue gases are purified by the reaction of SO_2 with a pulverised dry sorbent added into the system. The subsequent by-product is taken away as dry salt by a dust precipitator downstream of the furnace. Generally, the sorbents used are hydrated lime, limestone and dolomite. The dependency of the additive can be performed in three ways: by adding it to the fuel, adding it to oxygen, and adding it to the fire location. This procedure accomplishes a SO_2 reduction efficiency of 50% between 750°C to 1250°C and can be utilised for fuels with a sulphur content of up to 1% (Gupta *et al.,* 2016). On the other hand Sarkar and Sarkar (2015) believed that dry sorbent injections are capable of capturing from 40% to 80% of the SO_2 between 760°C to 1090°C whereas Laird *et al*. (2012) were able to capture 99.96% of acid gases at 343°C.

Although Marocco and Mora (2013) did not suggest a removal efficiency, they mentioned that the quantity of $Ca(OH)_2$ utilised in DSI is typically three to four times the amount hypothetically expected for the total reduction of gaseous pollutants. This was as a result of high dosage of hydrated lime required for the treatment of both HCl and SO_2. Arena (2015) reported that numerous incineration facilities in Europe have adopted the dry sorbent injection technology to capture more than 99% of HCl and more than 90% of SO_2 with sodium bicarbonate not with hydrated lime as stated by Laird *et al.* (2012) and Gupta *et al*. (2016).

2.10 Effect of Hydrated Lime on Mercury

Hydrated lime injections with DSI have both positive and negative impacts on the reduction of Hg from flue gas. Mercury is not removed by hydrated lime but rather is influenced contrarily by HCl expulsion with antacid sorbents and aggressively from SO_3 reduction (Laird *et al.,* 2012). While it is self-evident that HCl in flue gas can help oxidise mercury, it is not clear yet whether, once oxidised, the presence of HCl is necessary to avert the reduction of Hg. Contrary to this, SO_3 tends to precipitate onto the pores of hydrated lime as flue gas is cooled. Its removal from flue gas keeps the pores of $Ca(OH)_2$ open to absorb Hg more effectively (Laird *et al.,* 2012).

2.11 The Impact of Temperature Reliance in Sorbent Injections

Hydrated lime assumes an important responsibility as a reactive agent. It is utilised mainly for the reduction of acid gas emissions at coal-fired electrical manufacturing stations (Dowling *et al.,* 2015). In Flue Gas Desulphurisation (FGD) operational modern facilities, electric plants and incineration facilities, lime is a major reagent of sulphur and chlorine oxides in the flue gas. Lime is additionally contemplated as an attainable sorbent for CO_2 reduction (Dowling *et al.,* 2015).

Hydrated lime is broadly used as a sorbent in dry and semi-dry sulphur reduction procedures. In the Laird *et al.* (2012), the studies were conducted at various coal fired power plants. The examination of the response of $Ca(OH)_2$ with synthetic flue gas demonstrated that the relative humidity of the gas has an important effect on the reactivity of $Ca(OH)_2$ (Laird *et al.,* 2012).

According to Laird *et al.* (2012), the general reactive temperature of $Ca(OH)_2$ with HCl, HF, SO_2, NO_2 and NO_x ranges between 121°C and 454°C. If both SO_2 and HCl needed to be captured through sorbent injections, $Ca(OH)_2$ would have to be injected at different flue gas temperatures depending on the degree of acid gas removal desired (Laird *et al.,* 2012). However, at Biomed the AEL conditions require that the temperature at start-up must first achieve 1200°C before any waste is incinerated and thereafter be kept between 850°C to 1200°C.

In the current study, the $Ca(OH)_2$ was injected at temperatures between 850°C and 1200°C for the capturing of HCl, HF, CO, SO_2, NO_x, and the reactivity for each gas was monitored. According to Guillena, Najera and Ramon (1995) as quoted by Mathieu *et al.* (2012), adsorption of SO_2 on CaO samples required by calcination of various limestone at high temperature of 800°C showed that the adsorption rate tends to decrease with the presence of oxygen. The emerging of a calcium sulphate layer that surrounds the calcium oxide usually causes the reduction on SO_2 adsorption. The reduction rate also restricts the diffusion of the SO_2 molecules inside CaO particles (Mathieu *et al.,* 2012). The best temperature for SO_2 adsorption was confirmed to be between 440 and 540°C with an adsorption capacity varying from 34.5 to 39.5 mg/g (Mathieu *et al.,* 2012).

Wu *et al.* (2015) noted that the thermal decomposition of hydrated lime generally occurs within a temperature range of 420°C to 510°C. They found that, within a temperature range of 600°C to 900°C, the average SO_2 concentration gradually increases. On the other hand, Liu *et al*. (2016) noted that when the temperature is above 700°C, the average SO_2 concentration significantly increases.

Liu *et al*. (2016) further stated that the best temperature for hydrated lime for the removal of HCl is between 600°C to 850°C. However, Liu *et al*. (2016) did not include the effectiveness of other gases. According to the findings by Laird *et al*. (2012), there may be an incompatible reaction between SO_2 and HCl if they are both captured at the same temperature.

Conclusions from past research are inconclusive about what temperature is required to capture acid gases using $Ca(OH)_2$. Both Astrup, Tonini, Turconi & Boldrin (2015) and Margallo, Taddei, Hern, Pell Aldaco & Irabien (2015) as quoted by Liu, Huang, Sun & Xie (2016) argued that the capacity of $Ca(OH)_2$ to capture acid gases expanded with the increase of temperature within the range of 400°C to 600°C. However, Astrup *et al*. (2015) and Steel and Patrick (2011) maintained that arsenic capture also expanded with the increasing temperature in the range within 600°C to 1000°C. The

conclusions from Margallo *et al*. (2015) are similar to Jiao *et al.* (2011): the acid gas captured increased at the temperature within 400°C to 600°C.

The temperature plays a vital role in neutralisation of gaseous emissions (Singleton Birch, 2014). At high temperature above 850°C $Ca(OH)_2$ is utilised for the reduction of SO_2 emissions at coal-fired manufacturing stations. In FGD serving industrial plants, electrical manufacturing facilities and incineration plants, temperature and lime are used to react with sulphur and chlorine oxides in the flue gas (Dowling *et al.,* 2015). Lime is also believed to be a practical sorbent for CO_2 reduction and is mentioned in an early IPCC Special Report (CML, 2016; Al-Awadhi and Al-Shuaibi, 2013).

2.12 Dry Sorbent Injection Testing Using Hydrated Lime

In the study done by Laird *et al.* (2012), $Ca(OH)_2$ was pneumatically injected into a venturi chamber and blended with a higher unconfined flue gas inside the internal duct of the reactor. The gas solid mixture was consequently compelled to stream down between the annular external reactor ducts to the rectangular release segment duct. After the outlet segment, the gases were moved using the fabric filter (Laird *et al.,* 2012).

In two of the three sites tested by Laird *et al*. (2012), there was an opportunity to introduce hydrated lime directly upstream and downstream of the unit's air pre-heater at temperatures ranging between 316°C and 343°C as well as 149°C and 177°C, respectively. The Environmental Protection Agency (EPA) Method 26A, which is the method used to determine emissions from stationary sources, was utilised to assess the baseline and managed concentrations of HCl downstream of particulate collection. As an alternative, the Transform Infrared (FTIR) instrument was also utilised to monitor various flue gas components including SO_2 and HCl. The third study area introduced $Ca(OH)_2$ directly downstream of the furnace at a temperature of 149°C and measured SO_2, HCl, and HF by a combination of Continuous Emission Monitoring Systems (CEMS) and FTIR (Laird *et al.,* 2012).

In the study to assess the reactivity of $Ca(OH)_2$ at high temperatures, Laird *et al.* (2012) injected approximately 11 tons of hydrated lime at the air pre-heater outlet with a feed rate of 8400 lbs/hr (3810 kg/hr). This brought about a rough reduction rate of 99.96% SO_2 and discharge rate of 2.5 lb/MMBtu, measured by EPA Method 26A (Laird *et al.,*

2012). This, however, contradicts Jiao *et al.* (2011) who concluded that the capacity of capturing more gaseous emissions increases as the temperature at which hydrated lime is injected also increases. Laird *et al*. (2012) were able to capture 99.96% of acid gases at 343°C while Jiao *et al.* (2011) were able to achieve 86% reduction efficiency.

In the study to assess the reactivity of $Ca(OH)_2$ at low temperatures, Laird *et al.* (2012) injected approximately 12 tons of hydrated lime at the entrance to the air pre-heater at different feed rates of 3800 lbs/hr to 7800 lbs/hr. The 3800 lbs/hr test brought about an injection of 0.006 lb/MMBtu and reduction rate of 91.7% of SO_2. The 7800 lbs/hr test brought about an injection of 0.001 lb/MMBtu, a reduction rate of 98.9%, which was within the 2015 Mercury and Air Toxics Standards (MATS) emission compliance target for the site (Laird *et al.,* 2012). As stated by Laird *et al*. (2012), although the $Ca(OH)_2$ was injected at low temperatures, the increase in feed rate aided in more gases being captured. That again contradicts Jiao *et al*. (2011) who stated that more gases are captured by increasing the temperature and not by increasing the hydrated lime dosage.

In another study Laird *et al.* (2012) injected approximately 12 tons of hydrated lime at the entrance of the APH over a two-day period at a feeding rate between 1440 to 3540 lbs/hr. This brought about a 94% reduction by FTIR and 96.8% reduction at a feed rate of 3380 lbs/hr utilising the EPA Method 26A, estimation (Laird *et al.,* 2012). These results still emphasise what Laird *et al.* (2012) concluded: that the increase in hydrated lime feed rate will increase the capacity in neutralising the gases.

Mathieu *et al.* (2012) indicated that calcium oxide formed sorbents sodium such as limestone, hydrated lime or lime (CaO) are amongst the most utilised sorbents for industrial desulphurisation with most FGD methods depending on two critical proficiencies, which are the wet and dry scrubbing. Approximately 95% of SO_2 is generally removed through $Ca(OH)_2$ sorbents (Mathieu *et al.,* 2012). Other calcium based natural materials such as dolomites were also assessed for the reduction of SO_2 but the efficiency cannot be confirmed (Mathieu *et al.,* 2012).

Hydrated lime injections, downstream of the furnace (upstream or downstream of the air heater) or scrubber can effectively reduce SO_3 emissions from 80% to over 99% (Miller and Miller, 2012). Duct sorbent injection removes SO_3 more efficiently than wet FGD scrubbers and captures HCl and HF. Dry hydrated lime is commercially utilised to lower SO_3 emissions and over 80% reduction has been achieved (Miller and Miller, 2012).

In a different study Morabito, Contini, Belosi, Stortini, Manodori & Gambaro (2014) did not include the impact of hydrated lime feed rate or temperature reliance in their study. They only mention that adsorption and absorption of acid gases especially HCl and SO_2 are still receiving most attention. Adsorption and absorption techniques are utilised for the reduction of gaseous emissions from municipal solid waste incineration processes and wastes containing chlorine (Morabito *et al.,* 2014).

2.13 Air Pollution Control Techniques in Modern Incinerators

Various existing municipal waste incineration facilities do not contain adequate air pollution control devices. Only a few have particulate control devices, which are often inefficient and conform to old standards for emissions of particulate matter. Newer ones contain both particulate matter and acid gas control equipment such as venturi scrubbers (Miller and Miller, 2011).

In the USA, the existing municipal solid waste incineration facilities are fitted with equipment for particulate matter, acid gases, and, mostly dioxin and mercury capturing. These treatment facilities mostly utilise fabric filters or dry electrostatic precipitators (ESP) for PM capturing and reduction. ESPs became well known in the early 1970s (Miller and Miller, 2011) however in the 1980s, fabric filters, generally known as bag houses, became well favoured, but ESP is the most favoured method for particulate reduction due to its enhanced potential for capturing smaller particles. Spray dryer absorbers and dry lime injection methods are utilised for acid gases such as HCl and SO_2 reduction. Dry powdered activated carbon injection systems are used for dioxin and furan and mercury reduction (Miller and Miller, 2011).

Miller and Miller (2011) agree with Chibante *et al.* (2010) who concluded that adsorption and absorption are still the most recognised methods of capturing gaseous emissions in combustion processes. On the other hand, Dowling *et al.* (2015) raised a concern over the lime industry. They stated that the challenge is the financial value in lime production, which increased because of the requirement for additional monitoring, reduction and control of air emissions such as hydrogen chloride and greenhouse gases, especially carbon dioxide. Since the demand is high, lime production companies have increased their prices drastically (Dowling *et al.,* 2015).

Hazardous waste incineration facilities in the USA have customarily utilised wet air pollution control devices. This method may not be a solution in South Africa due to the current shortage of water and frequent droughts. Wet scrubbing techniques use large quantities of water and produce large volumes of wastewater (Mathieu *et al.,* 2012). Of late, there has been a trend towards using fabric filter techniques especially in larger incineration facilities due to their level of fine particulate matter emissions and metal emission control efficiencies and their capacity to formulate a dry build-up compared to a scrubber wastewater stream. Wet ESP techniques may be recommended in the future for the capturing of particulates and compliance with emission control standards and regulations (Sarkar and Sarkar, 2015).

Cement kilns and coal-fired boilers that incinerate waste as fuelling agents have repeatedly used either fabric filters or dry electrostatic precipitators as dynamic reduction techniques. These yielding devices incorporate the neutralisation of acid gases by cement products and the recycling of cement kiln dust back into the process (Sarkar and Sarkar, 2015).

There is little research on $Ca(OH)_2$ and incineration facilities; nevertheless, studies on the use of $Ca(OH)_2$ have been conducted in steel or coal combustion, boilers and furnaces. The literature from these studies can be used in the incineration of healthcare risk waste since the combustion principles are indistinguishable. Miller and Miller (2011) stated that numerous old incinerators have at least particulate control devices; Biomed incinerator used in the current study, however, does not have any particulate or emission control device.

2.14 Legal Framework for Gaseous Emissions from Waste Combustion

In 2000 the European Union (EU) provided a Directive 2000/76/EC for the incineration of healthcare risk waste. It was generally prescribed from German guidelines, the 17th Ordinance for the establishment of the Federal Act on Emission Control of 1990 (Harrison, Berry & Paterson, 2010). A summary of the directive is presented in Table 2.2. After the European Landfill Directive, it was recommended that as many as 170 new incineration facilities in the United Kingdom be redesigned to achieve the 2020 target (Le Cloirec, 2012). As stated by Defra (2013), in 2010, there were 73 authorised

incineration facilities in the UK, 18 of which treated healthcare risk waste. As of May 2013, UKWIN (2013) announced that there were 32 authorised incineration facilities to treat and process municipality solid waste (Harrison *et al.,* 2010).

In South Africa, the new stringent air quality regulation is forcing incineration companies to reduce their emissions. Table 2.2 below further compares the three similar regulations in the EU, Germany and South Africa. The EU has provided its associates the opportunity to strengthen up the emission levels and the German government has often made use of this opportunity in the past (USEPA, 2012).

Table 2.2: Emission limits per day for waste combustion (Source: USEPA, 2012)

Parameters	**EU Directive 2000/7/76/EC**	**17th BImSchV of 19/08/2003**	**South Africa Regulation**
	EU Limits	USA Limits	SA Limits
Reference O_2	11%	11%	10%
Hg	0.05 mg/m^3	0.03 mg/m^3	0.05 mg/Nm^3
CO	50 mg/m^3	50 mg/m^3	50 mg/Nm^3
HCl	10 mg/m^3	10 mg/m^3	10 mg/Nm^3
HF	1 mg/m^3	1 mg/m^3	1 mg/Nm^3
NO_2 (NO_x)	200 mg/m^3	200 mg/m^3	200 mg/Nm^3
TOC	10 mg/m^3	10 mg/m^3	10 mg/Nm^3
SO_2 and SO_3	50 mg/m^3	50 mg/m^3	50 mg/Nm^3
Dioxins and furans	0.1 ng/m^3	0.1 ng/m^3	0.1 ng/Nm^3
Particulate matter	-	-	30 mg/Nm^3

Capturing of HCl and various acid gas emissions from incineration facilities and plants is of concern because of the recently recommended National Emission Standards for Hazardous Air Pollutants regulations. The proposed new standard will affect various industries including boilers and incineration facilities. DSI of calcium-based reagent is not new and has been utilised in the municipal solid waste and hazardous waste incineration facilities in Europe for many years. These new regulations are driving

some in the USA to rediscover DSI as a feasible low capital option to acid gas control (Sewell and Dickerman, 2012).

2.15 Dry Sorbent Injection in Flue Gas Incineration Plants

Dry sorbent injection (DSI) is mostly utilised to capture acid gases such as SO_3, HCl, SO_2 and HF from combustion flue gas in boilers (Liu *et al.,* 2012). Dry scrubbing methods reduce SO_2 gas emissions and are utilised predominantly in combustion facilities and industrial boilers, municipal waste incineration facilities, healthcare waste incineration facilities and some refinery processes (Marocco and Mora, 2013). In spite of the wet and semi-dry procedures, where absorption predominates because of the availability of a thick liquid film covering the particles, the essential procedure of acid gas capturing in dry scrubbers is adsorption. Contaminant gas molecules attach itself to the floor surface of the highly responsive alkaline particles, where the reaction occurs (Marocco and Mora, 2013).

The alkaline sorbent targeted to capture acid gases is hydrated lime, which is pneumatically injected in the form of a fine powder. These sorbents have a large particulate surface area to assist in capturing of gaseous emissions. The disadvantage of dry sorbent injections is that the injection adsorption is not ideal for a very large utility due to the additional adsorbent required (Marocco and Mora, 2013).

Acquistapace, Marini and Corrente (2014) stated that the total amount of gaseous emissions generated by the treatment of healthcare risk waste can be captured through various upgrades to increase the effectiveness of the incineration plant. However, that does not mean that gases will not be generated. As much as the effectiveness and the maintenance of the incinerator is important, acid gases still require reduction to achieve air quality standards. Enhancing plant effectiveness can help to control the pollutants but emission reduction methods like dry sorbent injections are still needed for the capturing and the reduction of acid gas emissions.

The wet and dry scrubbers utilised at incineration facilities for acid gas and particulate reduction methodology are very big and expensive. As a result, dry sorbent injection of sodium sorbents has been revealed as an essential SO_2, HCl and mercury reduction strategy because of its low capital expense, small implementation impression, ease of use, and adaptability to different fuels. In actuality, numerous incineration facilities in

Europe have embraced this technique to capture more than 99% of HCl and more than 90% of SO_2 using sodium bicarbonate (Kurukulasuriya, Mendelsohn, Hassan, Benhin, Deressa, Diop, Eid, Fosu, Gbetibouo, Jain, Mahamadou, Mano, KabuboMariara, El-Marsafawy, Molua, Ouda, Ouedraogo, Se´ne, Maddison, Seo & Dinar, 2011).

According to Kurukulasuriya *et al.* (2011), dry injection of sodium sorbents is able to achieve more reduction rates for HCl (>99%) and SO_2 (>90%). This technology has been accepted in numerous waste incineration facilities in Europe and numerous coal manufacturing power facilities in the USA. With the promulgation of new legislation, this will be a cost effective technique which is simple to utilise for waste incineration and energy boiler facilities (Acquistapace *et al.,* 2014). This technology has been effectively used at numerous waste incineration facilities in different countries (Miller and Miller, 2011; Dowling *et al.,* 2015; and Laird *et al.,* 2012)

2.16 Low Temperature Dry Sorbent Injection

Hydrated lime is fluidised in air and injected directly into the exhaust ducting. More than 99% of HCl, 95% HF and over 95% of SO_2 can be captured using hydrated lime (Barbhuiya *et al.,* 2009). The neutralisation reactions are as follows:

$Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O$
$Ca(OH)_2 + 2HF \rightarrow CaF_2 + 2H_2O$
$Ca(OH)_2 + SO_2 \rightarrow CaSO_3 + H_2O$
$Ca(OH)_2 + SO_2 + 0.5O_2 \rightarrow CaSO_4 + H_2O$

Modified into calcium chloride, calcium sulphite, calcium sulphate and calcium fluoride, the acidic gases are collected in bag filters as solids identical to the semi-dry scrubbing system. The excess hydrated lime can be recycled to enhance usage (Alahmr, Othman, Wahid, Halim & Latif, 2012). Apart from the substance of accessible $Ca(OH)_2$, the receptive surface area region is likewise a significant subject for reduction efficiency. The high level of fineness of industrial hydrated lime additionally builds the capacity in capturing of acid gas components (Alahmr *et al.,* 2012).

2.17 High Temperature Dry Sorbent Injection

Hydrated lime is injected directly into the furnace at temperatures of more than 850°C. The hydrated lime breaks down within 30 milliseconds to create a porous and very responsive type of quicklime (Shalaby, Zakey, Tawfik, Solmon, Giorgi, Stordal, Sillman, Zaveri & Steiner, 2012). The reaction that takes place is as follows:

$Ca(OH)_2 \rightarrow CaO + H_2O$

In the presence of oxygen, hydrated lime reacts with oxides of sulphur at temperatures below 1200°C to produce calcium sulphate. The hydrated lime likewise reacts with any HCl or HF present. Shalaby *et al.* (2012) are of the opinion that in general, the high temperature in the dry injection system technology can only reduce sulphur dioxide by 50% to 65%. The fundamental benefits of this technology are that it needs minimal capital and can be retrofitted quickly. However, in contrast, it also has moderately high absorbent expenses and is only appropriate where incomplete desulphurisation is needed. The reduction reaction residue and ash from the combustion process are disposed of in landfill sites (Shalaby *et al.,* 2012).

2.18 Conclusion

South Africa faces many environmental challenges, pollution and associated problems which are endemic to developing countries. The direct and indirect effects of air pollution have an impact across the country and a growing concern is the rising level of air pollution, mainly from industrial emissions and energy production. This concern is further exacerbated by the fact that it is proposed that compliance to the NAAQS is to be achieved by the year 2020. Adding to the environmental challenges in South Africa is the problem of trans-boundary air pollution which further exacerbates the air pollution and environmental challenges due to its complexity and associated effects.

Due to global air pollution problems, POPs and stratospheric ozone depletion caused mainly by trans-boundary pollutants, air quality management in South Africa is of an international standard. The country is a party to various global treaties such as the UNFCCC, the Kyoto Protocol, Montreal Protocol and the Stockholm Convention in a bid to reduce the impacts of air pollution on the atmosphere, a shared global resource.

It is apparent that air quality management is a significant issue in the country which requires efforts from various stakeholders for the achievement of sustainable development, compliance to national standards, international best practice and above all, an environment that is not harmful to health and wellbeing.

From the different studies reviewed, it is demonstrated that hydrated lime is an effective sorbent for sodium in boiler and steel industries to reduce gaseous emissions. This technology could assist South Africa and other African countries who are still struggling with gaseous emissions. In various studies conducted by Laird *et al.* (2012) and Liu *et al.* (2012), hydrated lime was found to be an essential product in most cases and was mostly utilised as a dry sorbent injection in a spray reactor to reduce HCl and SO_2. Hydrated lime was injected directly into the flue gas to remove gaseous emissions at high temperatures. This reduction technique was mostly observed to have low transformation effectiveness and involves high lime consumption and production of a large amount of fly ash as a solid waste.

Bhattacharya, Chakraborty, Tuteja & Patel (2013) found that during the treatment of healthcare risk waste under the high temperature intervals, the reactivity of SO_2 and NO_2 expanded as the reactivity of HCl reduced as an after effect of the reactivity alkalinity with the other acid gases. However, the fraction of the hydrated lime converted by SO_2 increased as the SO_2 and HCl feed ratio increased. With more oxygen present in the system, more SO_2 was captured (Bhattacharya *et al.,* 2013).

Bhattacharya *et al.* (2013) concluded that the utilisation of hydrated lime in the three main flue gas treatment processes of dry, semi-dry and wet processes demonstrated its adaptability and versatility in reducing gaseous emissions. They found that the effective plant maintenance and $Ca(OH)_2$ dosage are the most cost-effective sodium sorbent that can be utilised to control gaseous emissions during the treatment of healthcare risk waste. Hydrated lime can provide a cost effective and a proficient solution to reduce of flue gases generated from incineration treatment processes. This study will explore these findings and will also investigate the level of reactivity of $Ca(OH)_2$ with various acid gases at different temperature intervals.

Chapter 3: Research Design and Methods

This chapter describes the research methodology used to collect and analyse data. It discusses the design, material and methods of study. The instrument used to collect data, methods that were implemented and maintenance of validity and reliability of the instrument are explained.

3.1 Research Design

The research was informed by a quantitative research design, which defines quantitative research as a traditional, impartial, precise method for gathering numerical data about a study, displayed in quantifiable form, and analysed through the work of statistics. It is utilised to depict and to describe correlations, or to analyse the similar situations and cause-and-effect correspondences. Quantitative research is concerned with quantities, perception, and the relationships between situations or numbers (Babbie and Mouton, 2012).

The quantitative design draws heavily on deductive reasoning in which data is collected, analysed, compared to the requirements and interpretation made based on the findings (De Vos, Strydom, Fouché & Delport, 2012). Quantitative strategies create data that can be aggregated and examined to portray and anticipate relationships (Babbie and Mouton, 2012). Experimental research was undertaken to establish the efficiency of hydrated lime in reducing and capturing acid gas emissions. This was done through continuous monitoring of acid gases following the injection of hydrated lime in the flue gas at high temperature over a duration of ten months from October 2016 to July 2017.

3.2 Data Generation

3.2.1 Introduction

This research relied on two data sets – secondary data primarily gathered by Biomed from October 2014 to July 2015; and primary data generated during this research from October 2016 to July 2017. Emissions data for the two periods was for regulated acid

gases, that is, HCl, CO, SO_2, NO, NO_2, HF, and particulate matter. The Procal 2000 IR Emissions Analyser (as seen in Figure 3.1) used to generate primary data during the course of this research is the same instrument which was used by Biomed to gather 2014/15 data. The two data sets were also generated under the same conditions.

Figure 3.1: Procal 2000 IR Emissions Analyzer (Magnified Picture) (SI Analytics, 2017)

3.2.2 The Instrument

Procal 2000 Analyser is an active sampler designed to provide an In-Situ analysis of up to six gas phase emission components simultaneously. According to NEMA: AQA requirements, acid gases must be measured using an International Organisation for Standardisation (ISO) 17025 authorised instrument for high precise pollutant measuring for a different range of emission components. ISO 17025 is the standard for which laboratories must hold accreditation in order to be deemed technically competent to measure and monitor the regulated gases. The Procal 2000 IR Emissions Analyser is one of South African National Accreditation System (SANAS) approved accredited emission monitoring equipment and was the only equipment used to collect primary data in this study.

The instrument was manufactured by Kittiwake Procal, Peterborough, United Kingdom. This continuous monitoring equipment was mounted directly on the stack for regulatory monitoring compliance. The instrument is heat resistant and was fully pre-engineered for maximum uptime measuring of multiple components simultaneously. The instrument has a gas analyser that provided precise, reliable continuous analysis of process gas down to ultra-low parts per million levels. It consists of a sample probe, filter, sample line (umbilical), gas conditioning system, calibration gas system and a series of gas analysers which indicates the parameters being measured as seen in Figure 3.2.

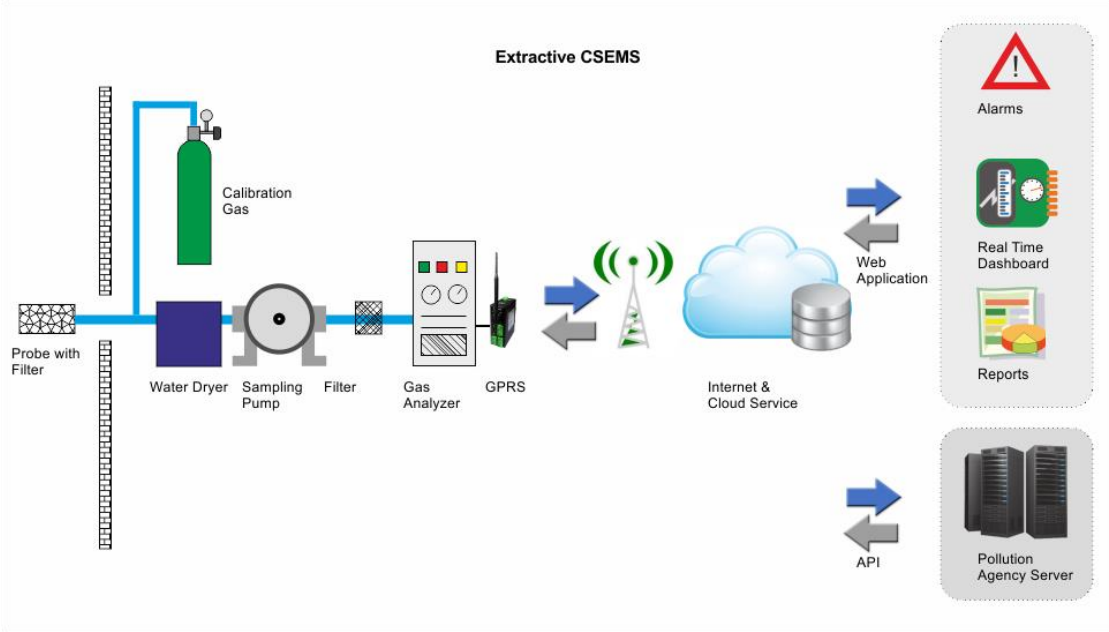


Figure 3.2: Extractive CSEMS (SI Analytics, 2017)

3.2.3 Secondary Data

The secondary emissions data for HCl, CO, SO_2, NO, NO_2, HF and particulate matter was extracted from previous Biomed stack emission reports. The data was generated before the $Ca(OH)_2$ intervention from October 2014 to July 2015. The reports were

compiled by SI Analytics with the information extracted from Procal 2000 IR Emissions Analyser.

The difference between secondary and primary data was that, there was no sorbent used when the secondary data was collected and $Ca(OH)_2$ was used as an intervention during the collection of primary data. The secondary data was then compared to the data collected after the intervention to evaluate the effectiveness of $Ca(OH)_2$ in reducing acid gas emissions and to determine the correlation between $Ca(OH)_2$ injections and particulate concentration.

3.2.4 Primary Data

3.2.4.1 Sampling

The following gases were measured HCl, CO, SO_2, NO, NO_2, HF and particulate matter and were expressed in mg/Nm^3 hourly average as prescribed in the Atmospheric Emission License. The regulated gases were monitored to ensure that a set maximum concentration per gas allowed in the ambient air was not exceeded. According to Section 21 of NEMA: AQA 39 of 2004, incineration facilities are regarded as listed activities, meaning these activities result in atmospheric emissions and which the Minister or MEC reasonably believes have or may have a significant detrimental effect on the environment, including health, social conditions, economic conditions, ecological conditions or cultural heritage. Therefore, according to the standard these gases require continuous monitoring.

Primary data was generated from the main stack. The Procal 2000 IR Emissions Analyser was mounted to the main stack (Figure 3.3.) to measure the emissions dispersed into the atmosphere since the emissions and particulate matter from flue gas are dispersed to the atmosphere through the stack (stationary source). The Procal 2000 Analyser is an active sampler designed to provide an In-Situ analysis of up to six gas phase emission components simultaneously.

After a successful monthly calibration of all units the instrument recorded findings for each unit every minute. The collected data was downloaded and reported as hourly averages. SI Analytics compiled monthly reports using the daily averages and adjusted the findings to 10% O_2 to ensure there was no dilution of pollutants with oxygen.

Figure 3.3: Main stack where samples were collected (Themba, 2017)

3.2.4.2 Data generation

At the incineration facility, the combustion of healthcare risk waste occurred in dual phases. In the initial phase, waste was kept in the primary chamber as seen in Figure 3.4 which was controlled with less stoichiometric oxygen needed for combustion components. The oxygen was introduced in the primary chamber from underneath the furnace. During this phase, the flue gas temperatures were generally between 850°C and 950°C (Howden, 2011).

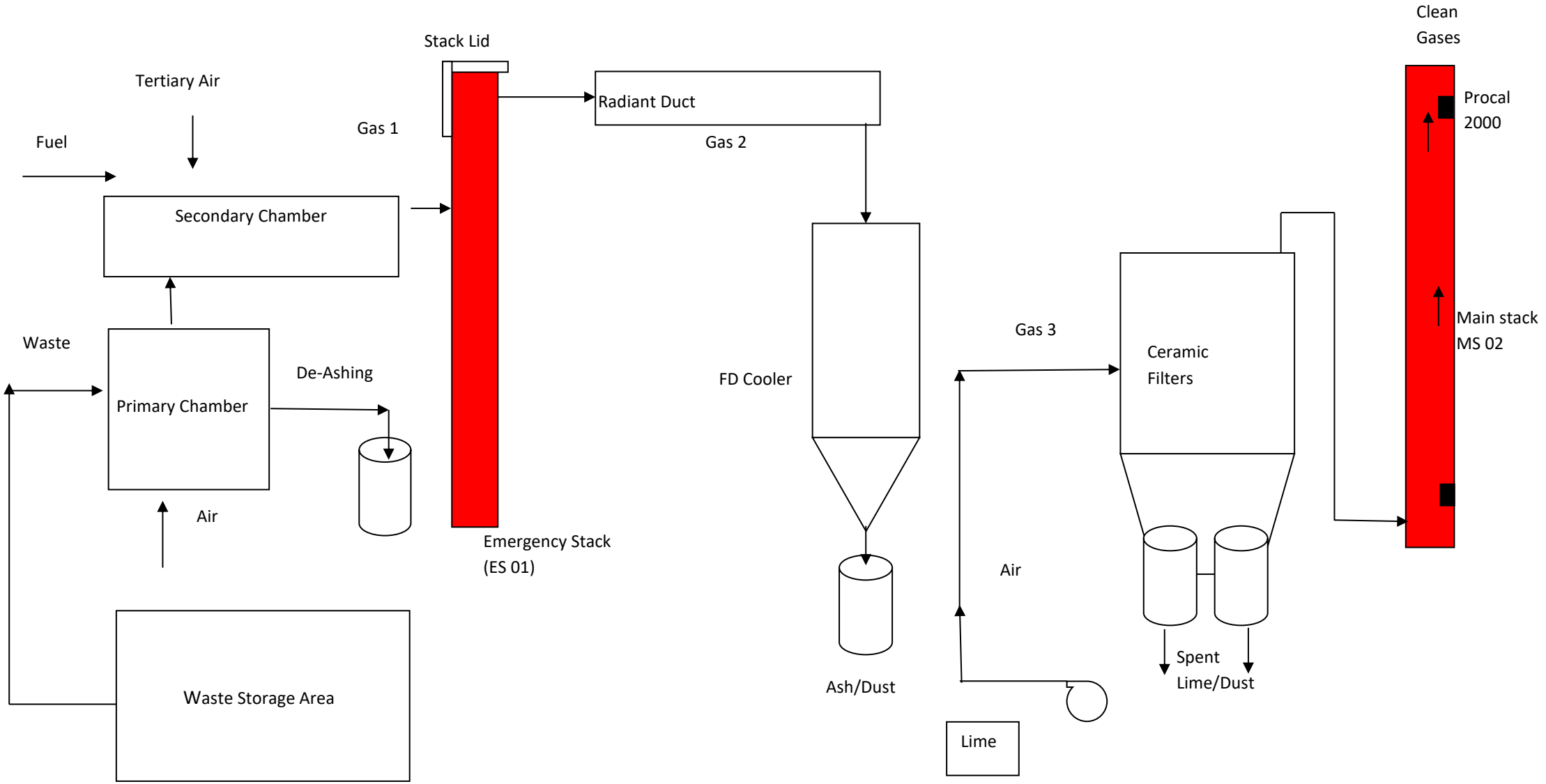


Figure 3.4: Process Flow and Point Sources Diagram (Source: Saner, 2012)

In the second phase, abundant oxygen was introduced to the volatile compounds created in the primary chamber to increase the temperatures. The temperature in the secondary chamber was maintained between 950°C and 1200°C. Based on the temperature values and the amount of humidity present in the material, more heat was introduced. This was provided by means of two auxiliary burners situated at the entry hole of the secondary chamber and two other burners on the primary chamber to provide the required temperature as reflected in Figure 3.4.

Every ten minutes, 100 kg of healthcare risk waste was fed to the incinerator as per the manufacturer's guidelines and the temperature was kept between 850°C in the primary chamber and up to 1200°C on the secondary chamber as required by the atmospheric emission license (AEL). The gaseous emissions together with dioxin and furans generated in the primary chamber during the combustion process were channelled to the secondary chamber where they were also combusted at 1200°C to reduce the amount emitted to the atmosphere.

During the study, 60 kg of sorbacal hydrated lime was injected on the lime feeder per day as per the maximum capacity for a lime feeder to allow the system to remain in gravimetric mode. The variable speed drive was used to inject hydrated lime into the furnace. The variable speed drive (VSD) was first adjusted from 1 kg/h however after 12 hours there was no reaction observed, it was then adjusted to 2 kg/h, still there was no reaction. It was then adjusted to 2.5 kg/h, only then the reaction was observed. Thereafter the dosage rate was kept between 2.5kg/h and 3.5 kg/h. The reaction of $Ca(OH)_2$ with acid gases was measured and analysed. The main justification of utilising a deductive approach was to assess whether $Ca(OH)_2$ was a successful method in reducing acid gas emissions.

Two manual blowers were used to provide continuous circulation of hydrated lime into the reaction chamber and to the dry scrubber. Four burners were utilised to ensure the furnace achieved the recommended temperatures and kept within the prescribed temperature intervals. Temperature readings from both primary and secondary chambers were also downloaded and collected from the temperature logger situated inside the plant next to the main distribution board.

The lime feeder was installed in a manner that it provided an uninterrupted flow of sorbacal $Ca(OH)_2$ (see Figure 3.5). It was able to carry a maximum of 60 kg of $Ca(OH)_2$ to increase the time the feeders stay in gravimetric mode. A rotary valve controlled by a variable speed drive connected to the panel was installed to the hopper outlet and

operated as a metering device. The valve released the sorbent across a small, vented chute straight into a revolving airlock running at a low velocity.

A variable speed drive (VSD) was used to measure the dosage of $Ca(OH)_2$. A VSD is a type of an adjustable speed drive utilised as part of electro-mechanical drive processes to operate a motor speed and torque by changing the motor input concentration and voltage. The VSD utilised drive controller with motors differing in size from about 2.5 kg/h to 5.0 kg/h. The speed was monitored by alternating the frequency of the electrical supply to the motor. The motor's rotor position and speed were progressively monitored by means of a resolver or digital encoder to evaluate and monitor the motor's velocity and torque.

A logbook was used to record the feeding rate data collected hourly. Plant operators checked and recorded the feeding rate every hour. The temperature readings from the primary and secondary chamber were collected and downloaded from the temperature logger. The temperature logger took readings every hour and a daily average was calculated.

Figure 3.5: Lime feeder (Themba, 2018)

The primary data was generated from a single sampling location in the main stack (MS02) as shown in Figure 3.3 using a continuous monitoring (structured data collection instrument). The regulated gases were monitored to ensure that a set maximum concentration per gas allowed in the ambient air was not exceeded.

The Procal 2000 Analyser (shown in Figure 3.1) managed and processed the raw data. It created and translated concentration readings in mg/Nm^3 measuring acid gases, moisture, humidity, velocity, exit temperature and particulate matter. The monitoring instrument measured the concentrations of all acid gas emissions over 24 hours a day for ten months. The instrument gathered a sample of all parameters every minute and the daily average was calculated and presented as findings. The emission findings were assessed to check if the minimum standard recommended was achieved.

During the study, a small sample of flue gas was extricated, using a calibrated pump, into the CEM framework through a sampling probe. A sample was then passed within a sample line (ordinarily alluded to as an umbilical) which separates analysers to remove a sample. Gas analysers used different strategies to calculate the concentrations known as infrared and ultraviolet adsorption. After the analysis, gas exited the analyser to a manifold where it was released out of the stack. A Data Acquisition and Handling System (DAHS) received data from the analyser and measured and monitored all emissions exiting the stack. To ensure the validity and reliability of the findings, instrument was maintained and calibrated on monthly basis only by SI Analytic and the maintenance and calibration reports were provided.

3.3 Data Analysis

In order to evaluate if there was an optimum dosage rate of $Ca(OH)_2$ required to reduce acid gas emissions and to confirm the effectiveness of $Ca(OH)_2$ in reducing the emissions, a statistical analysis was performed. Comparative analysis was done to compare gas emission levels before and after the use of hydrated lime. Descriptive statistics were used to compute the mean, frequency and percentages. Excel linear regression analysis was done to test whether hydrated lime dosage had an effect in controlling gaseous emissions or not. While Wilcoxon signed-rank test and sign test were performed to test for any significance in emissions after the intervention. The objectives were addressed as follows:

3.3.1 Evaluating the Optimum Dosage Rate of $Ca(OH)_2$

Excel linear regression analysis was performed using primary data collected in 2016/17 and secondary data collected in 2014/15. The linear regression calculator using the least squares method was used to find the line of best fit for a set of paired data. The line of best fit is described by the equation $\hat{y} = bX + a$, where b is the slope of the line and a is the intercept. This allowed the researcher to test the hypothesis H0 and come up with the conclusion whether hydrated lime dosage had an effect in controlling gaseous emissions.

The $Ca(OH)_2$ feeding rate was calculated and monitored to evaluate the optimum dosage rate. Dosage rates for $Ca(OH)_2$ injections were recorded from the lime feeder to investigate the dosage rate required to reduce acid gases. The dosage rate was compared with the emission results using an excel linear regression calculator for the least squares method to determine the rate at which lime dosage rates were most effective in meeting the recommended standard.

During the study, 60 kg of sorbacal hydrated lime was injected into the lime feeder over 24 hours. The variable speed drive was used to inject $Ca(OH)_2$ into the flue gas at 2.5 kg/h translating to 2,5 kg per hour. A VSD converted the 2.5 kg/h frequency and voltage auxiliary power supply into a distribution control supply, utilising an incorporated rectifier. Operators collected lime input data on the lime feeder everyday using a register that was created to monitor the lime consumption (Appendix 3). Data collected from the lime feeder was compared to the output emission measurements collected from the main stack. This was done by analysing $Ca(OH)_2$ feeding rates collected from the lime feeder every hour and comparing it with emission findings to determine the feed rate at which $Ca(OH)_2$ injections were more effective.

Fly ash measurements were collected and analysed by the emission analyser. The findings were analysed against $Ca(OH)_2$ input measurements collected from the variable speed drive to evaluate if $Ca(OH)_2$ injections had any impact on particulate properties. An hourly comparison was done between data collected before and after the intervention to determine the optimum dosage of lime rate at which more gaseous emissions were captured.

3.3.2 The Degree of Reactivity of $Ca(OH)_2$ with Different Gases at Different Temperatures

Descriptive analysis was used to provide descriptive characteristics of the data collected. Data was organised and summarised based on averages and ranges. The gas analyser produced data that was easy to compare, summarise, generalise and export to line graphs. To determine the level of reactivity of $Ca(OH)_2$ with different gases at different temperatures, the temperature data from the incinerator was collected from the temperature logger and was compared with emission results from the main stack after the intervention. The reactivity for each parameter was evaluated separately at different temperature intervals to evaluate the temperature at which the highest quantity of each gas was captured. The researcher studied the hydrated lime reactivity in different temperature intervals, compared data from the temperature logger and interpreted the findings.

Each parameter was analyzed to validate if daily concentrations were within the recommended limits or not. Bar graphs and tables were used to present the findings with a recommended daily average reflected by a red line. If the findings displayed on the graph were below the red line, it meant $Ca(OH)_2$ was successful in controlling those parameters below the recommended limits. If the findings were above the recommended line, it meant $Ca(OH)_2$ was less efficient in reducing those gases below the recommended standard.

3.3.3 Reduction in the Amount of Acid Gas Emissions

After the evaluation of reactivity of hydrated lime with different gases, the reduction in gas quantities were expressed in percentages. The emission measurements taken before the intervention from October 2014 to July 2015 were compared to the emission measurements taken after the intervention from October 2016 to July 2017. To determine the reduction in acid gases, a percentage analysis formula index was used to calculate each gas:

$$K = \frac{\text{2014/ parameters - 2016/ parameters}}{\text{2014 emission measurements}} \times 100$$

K = is the percentage reduction in acid gas emissions which figures were used.

2014/ parameters = are the emissions measurements collected in 2014/15 before the intervention.

2016/ parameters = are the emissions measurements collected in 2016/17 after the intervention.

To calculate the percentage index, the emission measurements collected after the intervention were subtracted from the emission measurements collected before the intervention. The difference was divided by the total emission measurements before the intervention per parameter multiplied by 100. Tables were used to capture the reduction rate achieved per acid gas per month and a bar graph was used to present the average reduction rate achieved per parameter.

3.3.4 Relationship Between $Ca(OH)_2$ Injections and Particulate Matter

The correlations between $Ca(OH)_2$ and particulate matter contaminants were assessed and outlined. The particulate matter was collected using Procal 2000 IR Emissions Analyser. The technology had the ability to measure particulate in the range from 0 to 450 mg/Nm³ per minute. The samples were collected using the extractive dilution system where a small gas sample was extracted from the stack. It then sifted particulates and diluted the sample with clean dry air. The diluted sample was then analysed by a high accurate analyser. The data was loaded on a continuous programme then uploaded to the server.

After the collection of data, properties of particulate matter collected before the intervention were compared to the data collected after the intervention to determine the impact and relationship between $Ca(OH)_2$ injections and particulate properties. The comparison was done using a comparative graph, measurements before the intervention were plotted in the blue column (bottom column) and the measurements after the intervention were plotted in the yellow column (top column).

3.3.5 Determining the Effectiveness of $Ca(OH)_2$ in gaseous emissions

Wilcoxon signed-rank test and sign test were done to test for any significance in the difference between emissions recorded before use of hydrated lime in 2014/15 and those recorded while hydrated lime was being used in 2016/17. De Vos *et al.* (2012) described Wilcoxon signed-rank test as a non-parametric statistical hypothesis test used to compare two related samples or repeated measurements on a single sample to assess whether the difference was significant or not. These tests allowed the researcher to test the hypothesis H1 and come up with the conclusion whether hydrated lime was significant in controlling gaseous emissions.The following formula was used:

Empirical Model: $M = \Sigma X / N$

Formula for the normal distribution:

$$f(x) = \frac{e^{-(x-\mu)2/2\sigma 2}}{\sigma \sqrt{2\pi}}$$

For a given mean (μ) and standard deviation (σ), plug in any value of x to receive the proportional frequency of that value in that particular normal distribution.

With sample taken from Population A being smaller than the sample from Population B) - reject H_0 if $T_A \geq T_U$ or $T_A \leq T_L$

Hydrated lime injections were used as an intervention to determine its effectiveness in capturing the acid gases. Emission readings were collected from the main stack where the sampling equipment was mounted as shown in Figure 3.6. Stack emission measurements required a characterised and stable stream condition at the sample point. This permitted the velocity and concentration of the measured parameters in the stack emissions to be determined.

Figure 3.6: Bottom of the main stack where the sampling instrument was mounted (Themba, 2017)

The efficiency of the CEM programme was exhibited in many ways. An inside quality confirmation validation was accomplished by daily presentation of a validated concentration of gas to the sampling probe. In addition, the Continuous Emissions Monitoring Calibration Systems, which dilute gases to produce calibration standards, was used.

The effectiveness of $Ca(OH)_2$ in reducing gaseous emissions was determined in two levels: first by comparing the emission findings with air quality standard to determine whether after the use of hydrated lime the emissions were reduced below the recommended limits and secondly by using Wilcoxon signed-rank test. Wilcoxon signed-rank test was performed to compare two samples, 2014/15 emission findings before the use of hydrated lime and 2016/17 emission findings after the use hydrated lime. Parameters from the same month were compared with each other to evaluate measurements taken before and after the intervention.

3.4 Reliability and Validity

Korb (2012) described reliability as the degree to which an assessment tool creates stable and consistent findings. He stated that reliability is important to ensure that the research is sound, free of bias and distortion. It ensures that if the same research was to be repeated, the results will be similar and the same conclusions will be reached. During the study, reliability was assured as the Procal 2000 instrument was managed and maintained by the SI Analytics engineer only. Biomed employees including the researcher received the training on how to operate the equipment and interpret data but were not given access to the instrument. One SI Analytics employee was tasked with the responsibility of downloading data and maintaining the instrument. Maintenance and calibration were done on site and the instrument was not moved around. The instrument room was always locked and only SI Analytics had access to it.

Data readings collected were viewed on the desktop computer situated in the Plant Manager's office. The readings were in an Excel portable document format (PDF) meaning that one can view and print the data, but no changes could be made on the document. The researcher could view the readings at any time via Team Viewer. Data on the temperature logger was only downloaded in PDF format. The researcher downloaded the data at the end of every month. Operators who recorded the feeding rates on the lime feeder were trained by the researcher to maintain consistency and reliability.

Korb (2012) described validity as how accurately a test calculates what is measured. While reliability was required, by itself, it was not adequate. For a test to be dependable, it also needs to be viable. The validity of the instrument was assured by calibrating the Procal 2000 IR Emissions instrument every month. The temperature logger was also calibrated once a year by GU Instrumentation and a calibration certificate was provided (see Appendix 6). Feeding rate measurements collected on the lime feeder were validated by the Plant Manager daily and spot check audits were conducted once a week by the researcher.

3.5 Justification

The instrument used to collect samples is recommended by ISO 17025. The parameters measured were the ones that required monitoring and reporting as regulated by Regulation 248 of NEMA: AQA 39 of 2004 which were HCl, CO, SO_2, NO, NO_2, HF, and particulate matter. The samples were collected only on the main stack because combustion gases are emitted to the atmosphere through the main stack. The emergency stack is only used during emergencies, for example, to release the gases from an aerosol cans explosion inside the primary chamber. The instrument was able to collect samples for all parameters every minute, and a daily average was calculated and presented as monthly reports by SI Analytics.

The equipment used was a continuous monitoring instrument and it collected samples over a period of ten months. Samples were preserved using an automated analysis that comes with the equipment. The measurements for all parameters could only be viewed through team viewer and changes to the data were not permitted.

3.6 Ethical Considerations

All ethical principles affiliated to this study were considered. Ethical clearance was granted by the University of South Africa, College of Environmental Science and permission to conduct the study was granted by Biomed (see Appendix 1 and 2). The researcher was truthful and impartial in all scientific communications and data collection. Data collected was not fabricated, falsified or misrepresented to display different findings. Intellectual property was honoured, and all patents and copyrights were respected. The author did not present other researchers' work as her own and gave proper credit for the work of others through citations. The final dissertation was also submitted for an originality check and it met all the requirements stated by the University of South Africa.

Safe storage was provided for the equipment. The handling of the monitoring equipment and components was safeguarded. Plant workers and staff were not permitted to open, fix or repair the monitoring instrument. The SI Analytics engineer was the only one who maintained and repaired the Electronic Procal 2000 IR Emissions Analyser. Data collected was used only for the purpose of the study and was not conveyed to people outside the research study.

3.7 Limitations of the Study

The study was cautiously organised but there were some unavoidable constraints. It should be noted, however, that the limitations identified did not compromise the validity and quality of the findings.

a) Secondary data - Secondary data was used for comparison as it was already available.

b) Plant shut down - Four minor shutdowns were scheduled for the 2017 financial year, which were planned for a maximum of eight hours per shutdown. The data was not collected during plant shutdowns as well as breakdowns. During shutdowns, the plant was not operational, and the monitoring instrument was not able to measure any parameters during that time. Data missed during shutdowns was reported as “no data” and daily averages were calculated for the remaining production hours worked.

c) Maintenance of the sampling probe - The sampling probe had to be taken out and cleaned at least once a week. During that period, the sampling probe was unable to collect data for a period of about ten minutes. If the probe is not properly maintained it will produce incorrect readings especially for particulate matter. A maintenance plan was implemented where the sampling probe had to be cleaned by the operators at least once a week. During maintenance, the sampling instrument would automatically switch off when the sampling probe was taken out. When the instrument was switched on again, it would only give an average of recorded measurements.

d) Power supply - The sampling instrument is power operated. Due to the construction that was taking place at Biomed facility to install a new non-burn technology machine, the power had to be disconnected for a day to perform an electrical connection test on a new transformer. During the power outage, the instrument was unable to collect readings. This only happened in May 2017 for a period of 12 hours and the daily average on this day was calculated over production hours worked.

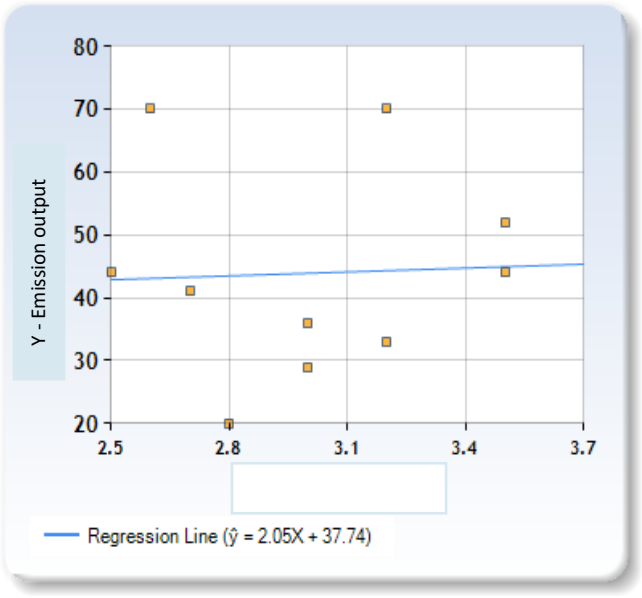
Chapter 4: Results and Discussion

4.1 Introduction

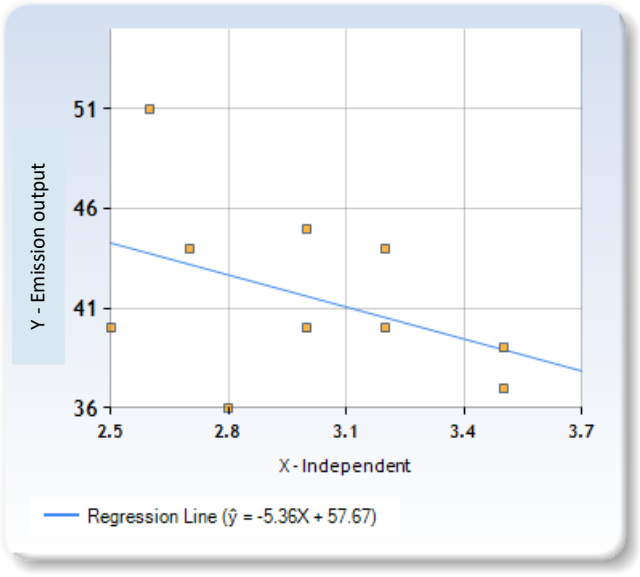
This chapter defines and depicts the results from the various methods described in the previous chapter. To note was that the emission measurements collected from the main stack were aimed at evaluating the effectiveness of hydrated lime in reducing gaseous emissions and also to assess the reactivity of lime with different gases at different temperature intervals and the relationship between the use of $Ca(OH)_2$ injections and particulate properties. Statistical analysis was performed on the results and the findings are presented according to the research objectives and research questions.

4.2 Evaluating the Optimum Dosage Rate of $Ca(OH)_2$

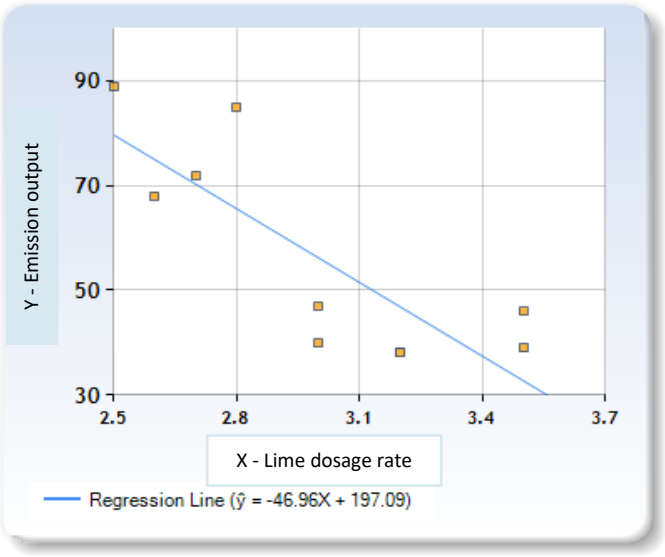
Hydrated lime injection rates were calculated and assessed to evaluate the dosage rate at which hydrated lime is most effective in reducing the gaseous emissions. Laird *et al. (*2012) define optimum dosage as the minimum quantity of a sorbent substance required to produce the desired stack emission concentrations for a specific unit without any unfavorable effects. The optimum dosage rates for $Ca(OH)_2$ injections were collected from the lime feeder to investigate the dosage rate required to reduce gaseous emissions. The dosage rate was compared with the emission results to determine the dosage rate at which the sorbent was mostly efficient. Linear regression analysis was used (Figure 4.1) to reflect a relationship between hydrated lime dosage rate and emission outputs. The dosage rate was kept between 2.5 kg/h and 3.5 kg/h as there was no reaction observed at 1 kg/h to 2 kg/h. Using Linear regression analysis the alternative hypothesis was accepted as it was found that there is a relationship between lime dosage rate and the reduction of gases and H0 null hypothesis was rejected.



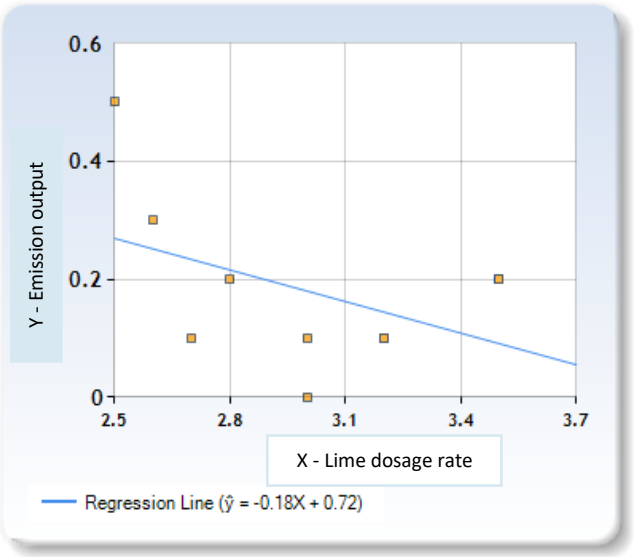
a. SO_2



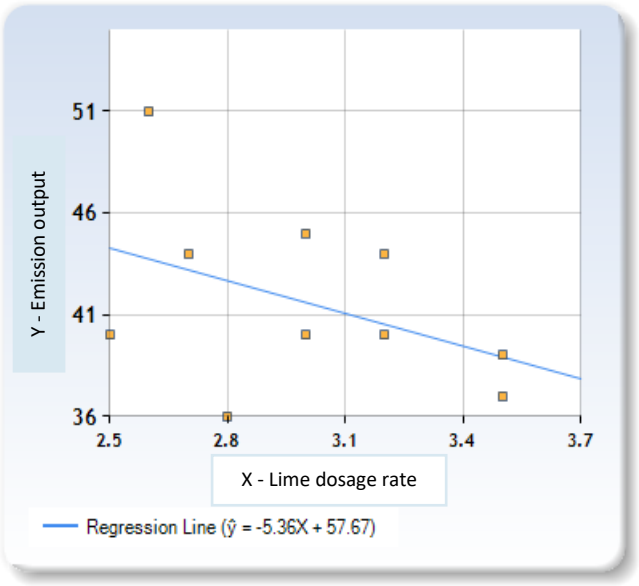
b. NO_x



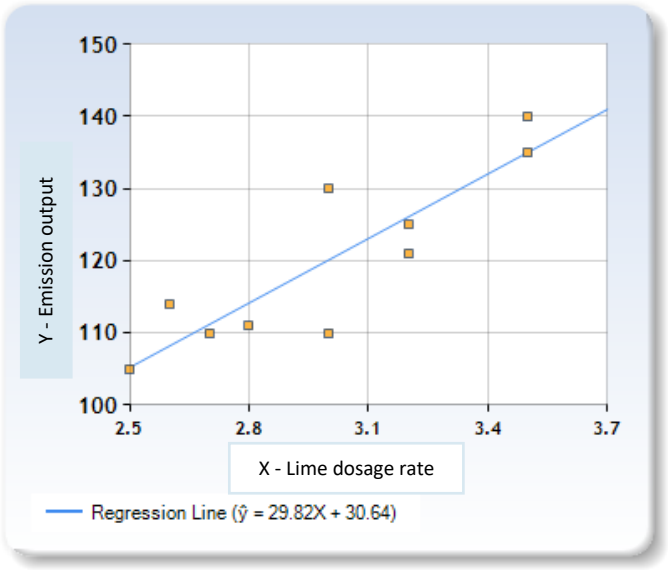
c. HF



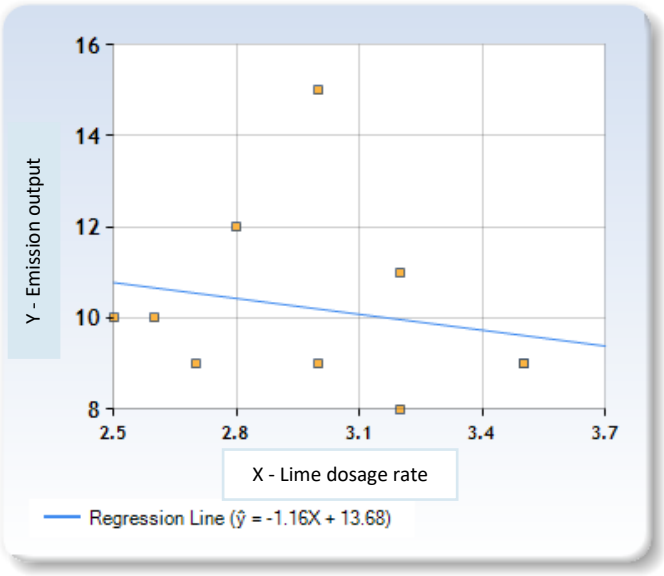
d. NO_2



e. CO



f. PM



g. HCl

Figure 4.1: Regression analyses of hydrated lime dosage rate and emission outputs

Figure 4.1a - g show findings reflecting the hydrated lime dosage rate at which different gases were captured. Most HF and HCl were captured at lime dosage rates between 2.5 kg/h and 3.5 kg/h. More NO_2 and particulate matter were captured between 3.2 kg/h and 3.5 kg/h. NO_x was captured between 2.8 kg/h and 3.5 kg/h while SO_2 reactivity took place between 2.8 kg/h and 3.5 kg/h.

It was discovered that an average of 60 kg of $Ca(OH)_2$ was required for the reduction of SO_2 per day. About 89% of SO_2 was captured using 2,5 kg of lime per hour. During the month of January 2017, about 108 kg of $Ca(OH)_2$ was used per month; however, only 75% of SO_2 emissions were captured (Table 4.2). This is because the effectiveness of hydrated lime for SO_2 reduction was strongly dependent on the amount of heat at the injection point. As more $Ca(OH)_2$ was utilised, the temperature at which the injections took place was rather low at 800°C; this confirms the dependency of SO_2 on high temperatures.

The addition of a calcium based sorbent $Ca(OH)_2$ inside the flue gas, over the burners at 1200°C reacted more with HCl, SO_2, and NO_x. Hydrated lime responded with sulphur dioxide and O_2, and was captured with the particulates in the fabric filter house. As indicated in Figure 4.1a, a reduction of over 87% of SO_2 was achieved at a sorbent feed rate of 3.0 lb $Ca(OH)_2$ per lb. Higher SO_2 reduction of 94% was achieved at maximised sorbent dosage rates of 2.7 kg/h and the fabric filter particulate collection device was utilised. The optimum dosage for SO_2 captured was found to be 2.7 kg/h.

The findings show that an average of 67 kg of $Ca(OH)_2$ a month was required for the reduction of NO_x. About 84% reduction was achieved at 1140°C temperatures; this was achieved due to the amount of sorbent utilised and 15% O_2 concentration. As the O_2 levels increased to 21% and the temperature to 1140°C, NO_x reduction also increased. About 108 kg of sorbent was utilised during the month of January 2017; however, only 86% NO_x reduction was achieved. This was approximately 2% more than what was achieved during February utilising only 67 kg of hydrated lime a month as demonstrated in Figure 4.1b. This shows that the high amount of SO_2 in flue gas during the month of January created competition between SO_2 and NO_x that led to more consumption of hydrated lime. The optimum dosage for NO_x was found to be 2.8 kg/h as reflected in Figure 4.1b.

The findings in Table 4.2 show that 83% reduction of NO_2 was achieved in March and 80% in June using an average of 76 kg of $Ca(OH)_2$. Reduction efficiencies were both achieved at high temperatures between 1140°C and 1200°C. As $Ca(OH)_2$ injections increased to 84 kg a month, NO_2 reduction also increased to 84% during the month of

July. The least NO_2 reduction was achieved during the month of January where only 55% NO_2 reduction was achieved. This was due to short residence time, low relative humidity at the low quantities of $Ca(OH)_2$ injection rate of 60 kg a month. Liu *et al*. (2016) reported that sorbent and sodium components maintained a higher reactivity at high temperature and high relative humidity. NO_2 reduction capacity was upgraded by another 10% with temperature at 1200°C. The optimum dosage for NO_2 was found to be 3.2 kg/h (Table 4.2).

The findings in Figure 4.1 and Table 4.4 show that 95% reduction of HF was achieved during December 2016. Hydrogen Fluoride is detected in healthcare waste from the explosion of aerosol cans. Due to high level of waste segregation in healthcare facilities, HF is found in small amounts of approximately less than 1 ppm. During December 2016, 0% HF was measured at 1020°C 3.0 kg/h $Ca(OH)_2$ feed rate and this was because of high dosage of hydrated lime. The low residence time in flue gas resulted in high consumption of $Ca(OH)_2$. The optimum dosage for HF was found to be 3.0 kg/h with high relative humidity. The degree that hydrated lime is reactive with HF depended upon the temperature at which hydrated lime and HF gas first come into contact (Laird *et al.,* 2012).

The optimum dosage for CO was determined in spite that $Ca(OH)_2$ injections did not influence the reaction of CO. There was no evidence on the relationship between $Ca(OH)_2$ injections and CO levels, however CO emissions were reported to have a relationship with temperature intervals. Essentially, CO, VOCs, and other organic compounds found in the flue gas of fossil fuel-fired units are primarily the products of incomplete combustion. Nalbandian (2012) found that the application of low-NO_x burners and flue gas recirculation decreases combustion efficiency, in some cases resulting in higher CO (Figure 4.1e).

However, BINE (2014) concluded that 60% CO emissions were captured using 2.1 kg/h hydrated lime injections. In their study CO was separated from other flue gases from power plants with the aim of achieving more reactivity. The technology was found to be expensive and time consuming. Another disadvantage of this method was that, the process reduced the efficiency of the power plant by 14% and the technology could not be retrofitted in existing power plant but can only be installed in new ones (BINE, 2014).

Manocha and Ponchon (2018) reported that 99% SO_2 were captured at 980^{o}C using 1.8 kg/h hydrated lime with 20% oxygen lancing from flue gas facilitates. The other

elements included Si, Mn, and P, were also oxidized and were absorbed in the slag layer captured (Manocha and Ponchon, 2018). This method however contradicted Laird *et al.* (2012) who concluded that more than 10% oxygen created dilution in flue gases and did not quantify the effectiveness of sorbent. Laird *et al.* (2012) injected lime at different temperature intervals using only 10% oxygen.

The findings show that particulate properties were highly influenced by $Ca(OH)_2$ injections. The findings support that the utilisation of $Ca(OH)_2$ increased the amount of PM by 31% as reflected in Figure 4.1f. Jones and Harrison (2016) also found that the introduction of absorbent and adsorbent materials into the process increased the particulate mass in the exhaust gases and increased the need for particle removal systems. The most common used methods for removing particles from the waste gas stream are cyclones, electrostatic precipitators and, on most recent MSW incineration installations, fabric filters or bag houses (Jones and Harrison, 2016).

Figure 4.1 illustrates the general reactivity of hydrated lime with different gases over a temperature range of 850°C to 1200°C. It was evident that if both SO_2 and HCl were treated through DSI, hydrated lime needed to be injected at various flue gas temperatures based on the degree of acid gas reduction required. HCl was highly reactive when hydrated lime was injected at temperature between 1190°C and 1200°C (Figure 4.1g).

The findings in Figure 4.1g and Figure 4.2 support that 97% HCl reduction was achieved during November, December, April, May, June and July. The $Ca(OH)_2$ feed rate varied between 2.7 and 3.2 kg/h (Table 4.2). The optimum dosage was found to be 3.2 kg/h with high residence time of 15 minutes and 3.5 kg/h, with short residence time of 8 minutes that brought about high consumption rate of $Ca(OH)_2$ per day. Hydrated lime was found to be an effective sorbent for controlling the HCl emissions.

Manocha and Ponchon (2018) found that 99% HCl was captured using 1.5 kg/h hydrated lime. The lime was injected through a centered additional hole together with 20% oxygen using a specifically designed lance. Manocha and Ponchon (2018) concluded that the benefits perceived were 100% recovery of the hydrated lime injected, improved dissolution rate of hydrated lime and improvement in the refractory lining life.

Patel, Lettieri & Germanà (2012) reported that they did not find any optimum lime dosage for gaseous emissions. Patel *et al.* (2012) concluded that hydrated lime can

be used to neutralize the acidic gases and remove SO_2, HCl, HF, CO and NO_x from flue gases at any dosage rate. The technology assisted Patel *et al.* (2012) to ensure the plants complied with both local and international environmental legislation for the environmental emissions. In conjunction with flue gas treatment equipment technologies, hydrated lime was the most cost effective and versatile sorbent that was used for this kind of treatment, with less dosage and less waste production compared with other reagents (Patel *et al.,* 2012).

4.3 The Degree of Reactivity of $Ca(OH)_2$ with Different Gases at Different Temperatures

Comparison between the emission findings and temperature intervals at which most emissions were captured are reflected in Table 4.1 and Table 4.2. Table 4.1 shows a comparison between data emission findings and temperature intervals captured in 2014/15 before the intervention and Table 4.2 shows a comparison between data emission findings, lime dosage rate and temperature intervals reported in 2016/17 after the intervention. As the combustion of gases occurred in the secondary chamber, it was noted that the majority of SO_2 was captured between 1000°C and 1020°C. As NO_x is a reactive gas, it was established that most of it was captured between 850°C and 920°C as reflected in Table 4.2.

NO_2 is a heavier gas and it was found that the majority of NO_2 was captured between 1140°C and 1200°C. HF is mostly generated in the beginning of the combustion process and it was established that the majority of HF was captured between 860°C and 920°C. As generally expected, more CO was combusted at high temperature of 1200°C. It was noted that more particulate matter was generated between 1000°C and 1200°C. HCl is also a reactive gas and the majority was captured between 1190°C and 1200°C.

Table 4.1 illustrates emission findings before the intervention and Table 4.2 presents emission findings after the intervention. The shaded columns are months where emission findings were above the limits. The recommended values are written in red.

Table 4.1: Comparison between data emission findings and temperature intervals in 2014/15 before the intervention

			Emissions in mg/Nm^3						
Sampling Period	**Primary Chamber °C**	**Secondary Chamber °C**	**SO_2 mg/Nm^3**	**NO_x mg/Nm^3**	**NO_2 mg/Nm^3**	**HF mg/Nm^3**	**CO mg/Nm^3**	**PM mg/Nm^3**	**HCl mg/Nm^3**
South African Air Quality Standard			50	200	200	1	50	30	10
Oct 2014	900	1160	350	249	210	2	186	80	250
Nov 2014	860	1170	290	265	198	2	160	90	300
Dec 2014	920	1200	344	244	195	2	200	65	260
Jan 2015	860	1000	285	218	210	1	154	79	289
Feb 2015	920	1020	253	289	224	2	189	96	315
Mar 2015	850	1140	330	280	218	1,5	120	80	223
Apr 2015	880	1190	337	190	235	1	100	70	417
May 2015	930	1200	378	230	220	2	160	70	328
Jun 2015	870	1200	250	250	199	1,9	130	100	315
Jul 2015	850	1200	350	280	250	1,7	150	78	265

Table 4.2: Comparison between data emission findings, lime dosage rate and temperature intervals in 2016/17 after the intervention

				Emissions in mg/Nm^3						
Sampling Period	**Primary Chamber °C**	**Secondary Chamber °C**	**Lime dosage rate kg/h**	**SO_2 mg/Nm^3**	**NO_x mg/Nm^3**	**NO_2 mg/Nm^3**	**HF mg/Nm^3**	**CO mg/Nm^3**	**PM mg/Nm^3**	**HCl mg/Nm^3**
South African Air Quality Standard				50	200	200	1	50	30	10
Oct 2016	900	1160	1.0	-	-	-	-	-	-	-
Oct 2016	900	1160	2.0	-	-	-	-	-	-	-
Oct 2016	900	1160	2.5	44	40	89	0.5	40	105	10
Nov 2016	860	1170	2.6	70	51	68	0.3	51	114	10
Dec 2016	920	1200	3.0	36	40	40	0.0	40	110	9
Jan 2017	860	1000	3.0	29	45	47	0.1	45	130	15
Feb 2017	920	1020	2.8	20	36	85	0.2	36	111	12
Mar 2017	850	1140	3.2	33	40	38	0.1	40	125	11
Apr 2017	880	1190	2.7	41	44	72	0.1	44	110	9
May 2017	930	1200	3.5	44	39	46	0.2	39	135	9
Jun 2017	870	1200	3.2	70	44	38	0.1	44	121	8
Jul 2017	850	1200	3.5	52	37	39	0.2	37	140	9

Note: - means no reaction observed

Table 4.1 demonstrates a secondary data collected before the intervention in 2014/15. It is evident that almost all gaseous emissions were reported to have been above the recommended limits. NO_x was reported to have exceeded the limit except during April 2015 where an amount of 190 mg/Nm^3 was reported. NO_2 was also reported to have exceeded the limit except in November 2014 where 198 mg/Nm^3 was reported, December 2014 where 195 mg/Nm^3 was reported and June 2015 where 199 mg/Nm^3 was reported. HF was reported to have exceeded the limit except during January 2015 and April 2015 where both measured 1 mg/Nm^3.

Table 4.2 presents emission results recorded in 2016/17 after the intervention. It is demonstrated that SO_2 only exceeded the limit during November 2016, June 2017 with both months each recording an amount of 70 mg/Nm^3 and July 2017 recording 52 mg/Nm^3. NO_x, NO_2, HF were all recorded to have been within the recommended limits. CO was only recorded above the limit in November 2016 recording an amount of 51 mg/Nm^3. HCl was recorded to have been above the limit in January 2017 measuring 15 mg/Nm^3, February 2017 measuring 12 mg/Nm^3 and March 2017 measuring 11 mg/Nm^3.

Table 4.2 demonstrates that most reactivity happened at high temperatures between 1150°C and 1200°C and also at low temperatures between 1000°C and 1050°C. More HCl reactivity happened between 1150°C and 1200°C, more HF reactivity was reported between 1000°C and 1200°C, more NO_2 was reported at 1200°C, and more SO_2 was reported between 1150°C and 1200°C.

A number of variables affected the reactivity of hydrated lime with any specific acid gas. Mainly there was competition in flue gas for hydrated lime among SO_2, NO_x, HCl and HF; but the degree that hydrated lime was responsive to these flue gases depended on the temperature at which hydrated lime first came into contact with the gases. Table 4.2 illustrates that HCl was more reactive between 1190°C and 1200°C. It was found that the adsorbent efficiency increased as the temperature on the flue gas increased. As the temperature increased, the pressure exerted on the adsorbent also increased bringing up the reactivity of HCl to its maximum capacity of 96%.

SO_2 was found to be more reactive at 1020°C as shown in Table 4.2. Hydrated lime reactivity with SO_2 increased at high temperatures and was heavily influenced by $Ca(OH)_2$ properties like surface area and injection rate. The reactivity of lime was also highly depended on temperatures. The reaction with SO_2 decreased as the temperature decreased. Patel *et al.* (2012) achieved the maximum efficiency of 97.7% at a temperature of 700°C, a Ca/S ratio of 3 and a velocity of 0.8 m/s. The lime particles

meant residence time was determined by an indirect method, which consisted of integrating the gas concentration curves normalized with respect to time.

NO_2 was found to be more reactive between 1120°C and 1200°C as demonstrated in Table 4.2. Chemical adsorption for NO_2 took place at elevated temperatures because of the influence of the NO_2 and NO_x chemical bond created during adsorption. It is confirmed that since high reduction of SO_2 was achieved, a high concentration of SO_2 in flue bed was generated, which led to high reduction rates of NO_2. The increase in NO_2 reduction was due to the solids forming a layer that prevented the alkaline products from reaching the surface to neutralise the acidic reaction components.

Yang, Cao & Yang (2017) achieved 88% HCl, 93% HF, 79% SO_2 and 83% NO_x between 950ºC and 1150 ºC. This happened as the value of pH in the process was increased to keep a consistent calcium oxide concentration, but the pH value of hydrated lime was secondary to the dew point temperature measurement to maintain the best flash reaction for the scrubber (Yang *et al.,* 2017). Xinhua (2017) reported that hydrated lime is only preferred when greater than 90% sulfur emission is required for the reduction of sulfur emission. Xinhua (2017) concluded that the great benefit of dry sorbent injections was the solid residue that occurred from the flash reaction at more than 1000ºC.

Table 4.2 reflects that NO_x was found to be more reactive at 1020°C. Higher relative humidity increased both SO_2 and NO_x conversion. Improvement in NO_x removal was also achieved when the stoichiometric feed ratio increased by 3% from 2.5 kg/h to 2.8 kg/h. This increased the total concentration of NO_x reduction to greater than 80% at full load. At a high temperature of 1020°C, the chemical reacted directly with oxygen to reduce more NO_x gases. The reduction of airflow through the burners decreased the formation of NO_x, and the greater the reduction in airflow, the greater the reduction of NO_x was observed.

HF was found to be more reactive at 1200°C. The maximum residence time between lime and flue gas was found to have high conversion efficiencies which brought about the low $Ca(OH)_2$ consumption rate but high HF reactivity. Many chemical adsorption processes took place at the temperature between 850°C and 1200°C.

Vanderreydt (2015) achieved the absorption efficiency of 62% NO_x, 76% HCl and 88% HF at 800ºC. He reported that the adsorption of NO_x, HCl and HF primarily took place on the outside of the calcium carbonate grains, the adsorption yield of the grains was relatively low. In order to increase the yield, Vanderreydt (2015) implemented a peeling

technique. This involved the softer outer-layer which was made up of calcium fluoride, calcium sulphite and calcium chloride being removed mechanically. The remaining grain was used again as adsorbent as it met the requirements (Vanderreydt, 2015).

Frank, Sparrow, Zoshi & Low (2017) described hydrated lime as a dry scrubber technology that is often selected when one wants to achieve between 50% and 65% sulfur gas reduction. In their study Frank *et al.* (2017) achieved 65% HCl, 63% HF, 59% SO_2 and 53% NO_x all at 1000^{o}C. Frank *et al.* (2017) described that dry scrubbing occurred because hydrated lime reacted in a rapid time frame called a flash process. Limestone (calcium carbonate) did not react with sulfur emission compounds at the same rate as hydrated lime, and this made hydrated lime the only feasible compound for utilization in a dry scrubber system, where a fast rate of chemical reaction was required (Frank *et al.,* 2017).

It is concluded that hydrated lime injections were able to reduce the gaseous emissions below the recommended limits. It is also concluded that the reactivity of hydrated lime with different gases at different temperature intervals was determined and was found to have a correlation.

4.4 Reduction in the Amount of Acid Gas Emissions

After the evaluation of reactivity of lime with different gases, the amount of gases reduced was quantified in terms of percentages. The emission measurements taken before the intervention from October 2014 to July 2015 were compared to the emission measurements taken after the intervention from October 2016 to July 2017. The temperature ranged from 850°C to 1200°C with $Ca(OH)_2$ dosage between 2.5 kg/h and 3.5 kg/h.

4.4.1 Hydrogen Chloride

Figure 4.2 demonstrates the comparison for HCl reduction when utilising hydrated lime injections between 2014/15 before the intervention and 2016/17 after the intervention. The highest HCl reduction achieved was 97% during the month of November 2016, December 2016, April 2017, May 2017, and June 2017. The least reduction was 94% during the month of January 2017.

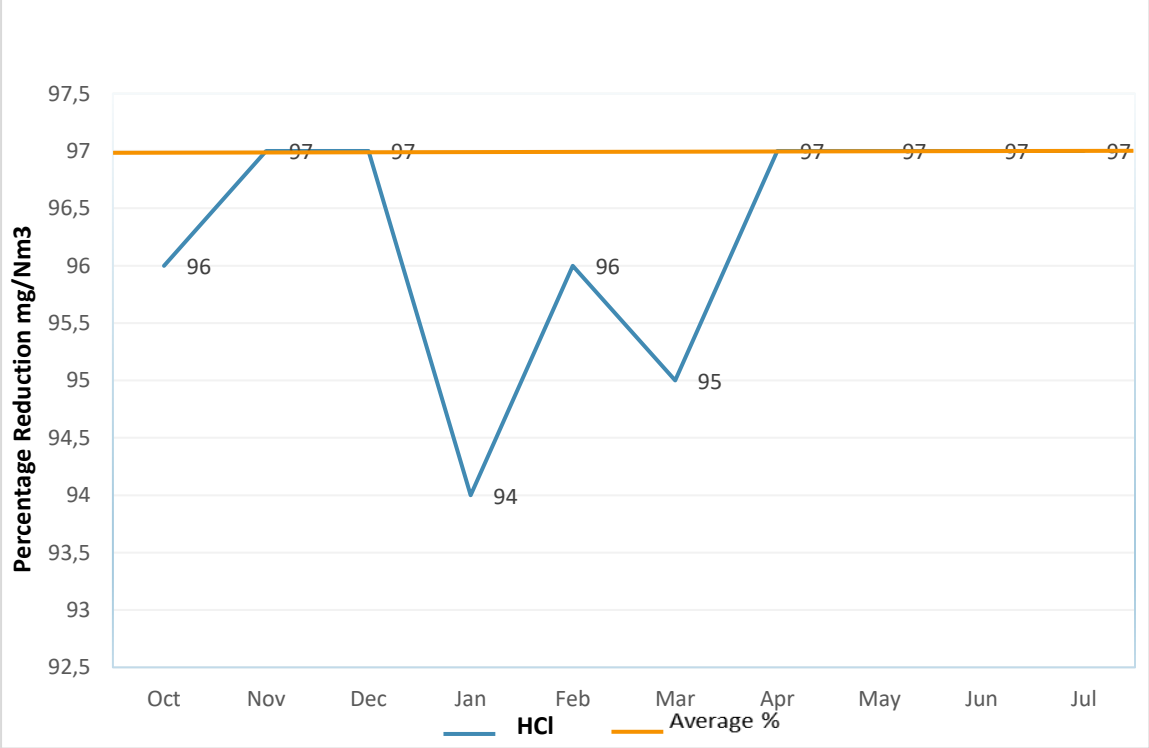


Figure 4.2: HCl percentage reduction between 2014/15 and 2016/17

The findings in Figure 4.2 show that an average of 97% HCl reduction was achieved. HCl also reacted with hydrated lime and is thus scrubbed from the flue gas. Sorbacal hydrated lime with small particle sizes stimulated more efficiency in controlling HCl. The lowest reduction in January 2017 was as a result of additional O_2 in flue gas which subsequently reduced the amount of temperature.

4.4.2 Hydrogen Fluoride

Figure 4.3 reflects the percentages for hydrogen fluoride reduction when utilising hydrated lime injections between 2014/15 before the intervention and 2016/17 after the intervention. The highest HF reduction achieved was 95% measured in December 2016 and June 2017. The least reduction was 50% measured in October 2016. The findings show that the average reduction of 86% HF was achieved. Although HF was detected in low quantities throughout the study, in October 2016 the highest amount of 0.5 mg/Nm^3 was measured. It was concluded that this amount was due to poor segregation of healthcare waste from domestic waste in hospitals.

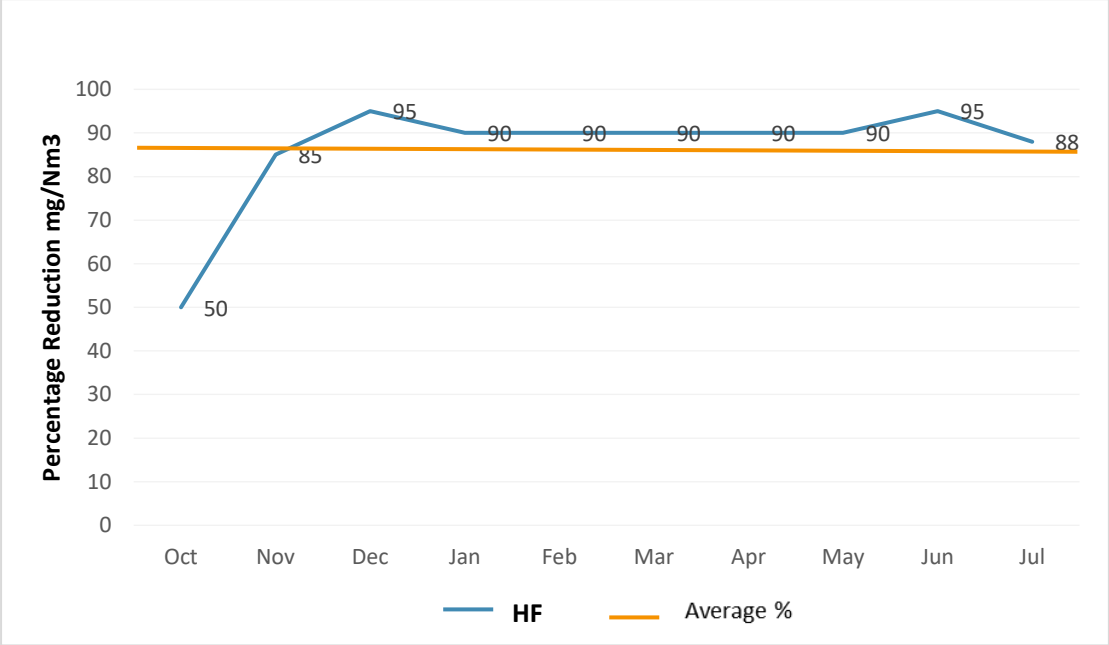


Figure 4.3: HF percentage reduction between 2014/15 and 2016/17

4.4.3 Sulphur Dioxide

Figure 4.4 reflects the percentages for sulphur dioxide reduction after the use of hydrated lime injections between 2014/15 before the intervention and 2016/17 after the intervention. The highest SO_2 reduction achieved was 94% measured in April 2017. The least reduction was 75% measured in January 2017.

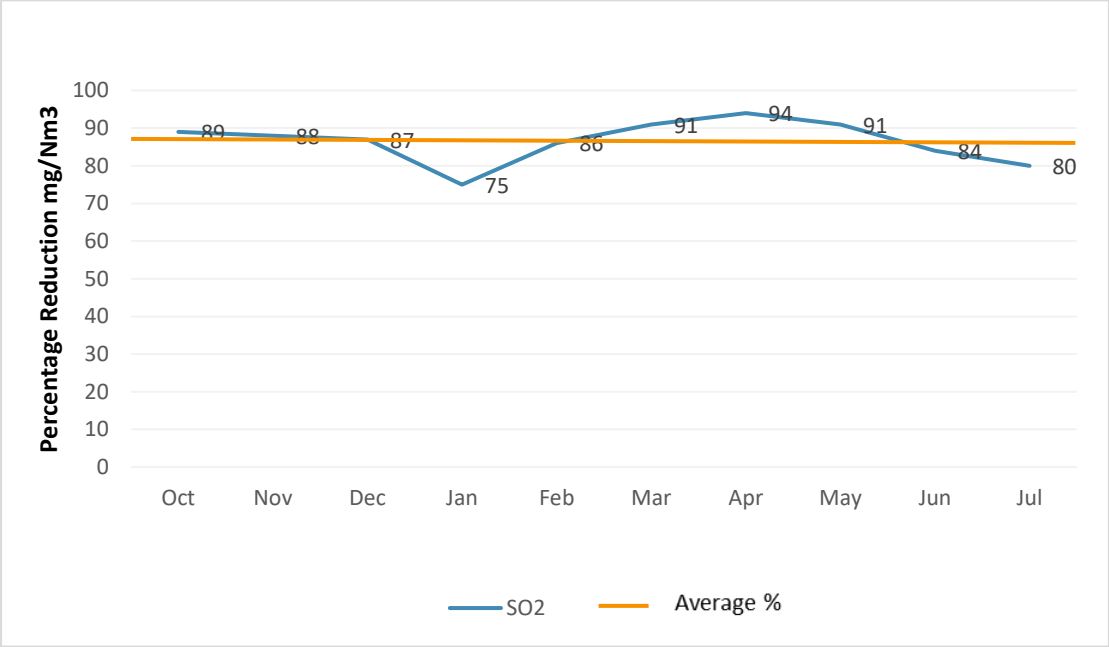


Figure 4.4: Sulphur dioxide percentage reduction between 2014/15 and 2016/17

It was found that the main operating variables controlling the sulphur dioxide adsorption on hydrated lime, in the absence of solid recirculation, were the calcium to sulphur molar ratio, SO_2 concentration in the flue gas, gas flow rate, specific particles surface area and the relative humidity. These operating variables aided in achieving a high reduction rate throughout the study. A decrease in the reduction was seen in January 2017 where an amount of 75% was achieved. It was concluded that reduction was as a result of the competition in flue gas between HCl and SO_2. The average SO_2 reduction achieved was 87%.

4.4.4 Nitric Dioxide

Figure 4.5 demonstrates the results for nitric dioxide reduction after the use of hydrated lime injections between 2014/15 before the intervention and 2016/17 after the intervention. The highest NO_2 reduction achieved was 84% measured in July 2017. The least NO_2 reduction was 55% measured in October 2016.

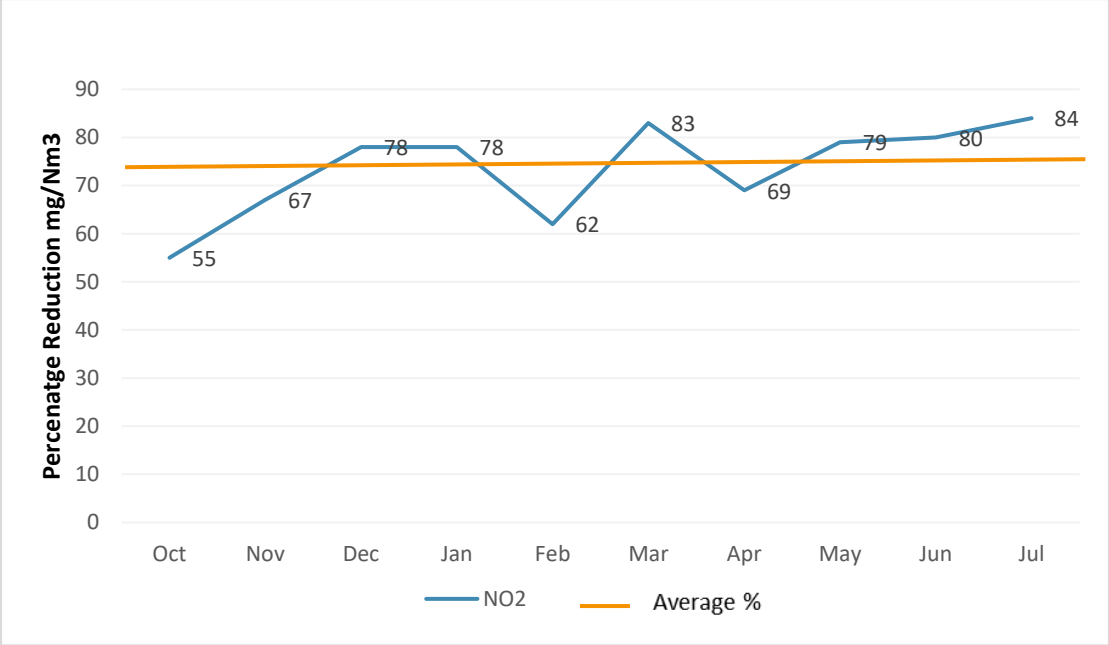


Figure 4.5: Nitric dioxide percentage reduction between 2014/15 and 2016/17

The findings in Figure 4.5 demonstrate that the NO_2 reduction increased marginally during the study. A low reduction was demonstrated in October 2016, November 2016 and February 2017. This was due to high moisture content from waste material and low residence time of eight minutes encountered. It was concluded that the average reduction of 74% was achieved.

4.4.5 Oxide of Nitrogen

Figure 4.6 demonstrates the percentages for oxide of nitrogen reduction after the use of hydrated lime injections between 2014/15 before the intervention and 2016/17 after the intervention. The average of 83.3% was achieved for NO_x reduction. It was noted that the reduction of NO_x increased magically during the study. The least reduction was reported in April 2017; this was due to low O_2 concentration of 15% encountered. The highest NO_x reduction achieved was 88% measured in February 2017. The least reduction was 78% measured in April 2017.

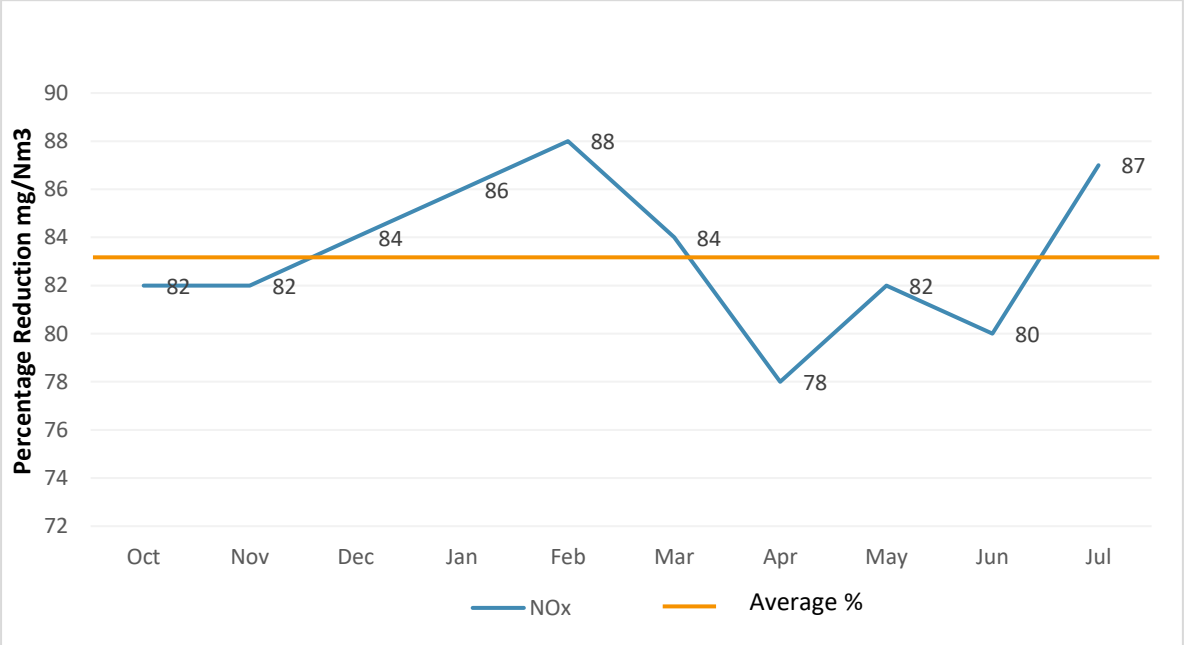


Figure 4.6: Oxide of nitrogen percentage reduction between 2014/15 and 2016/17

4.4.6 Carbon Monoxide

Figure 4.7 shows the percentage reduction of carbon monoxide reduction after the use of hydrated lime injections between 2014/15 before the intervention and 2016/17 after the intervention. The highest CO reduction achieved was 81% measured in February 2017. The least reduction was 56% measured in April 2017.

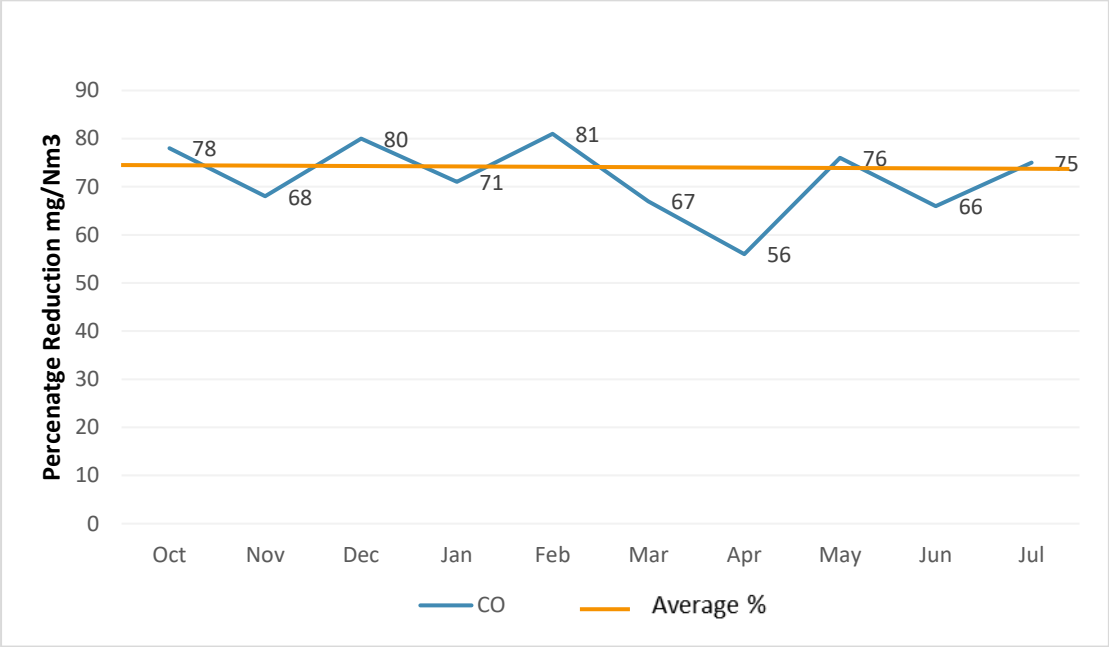
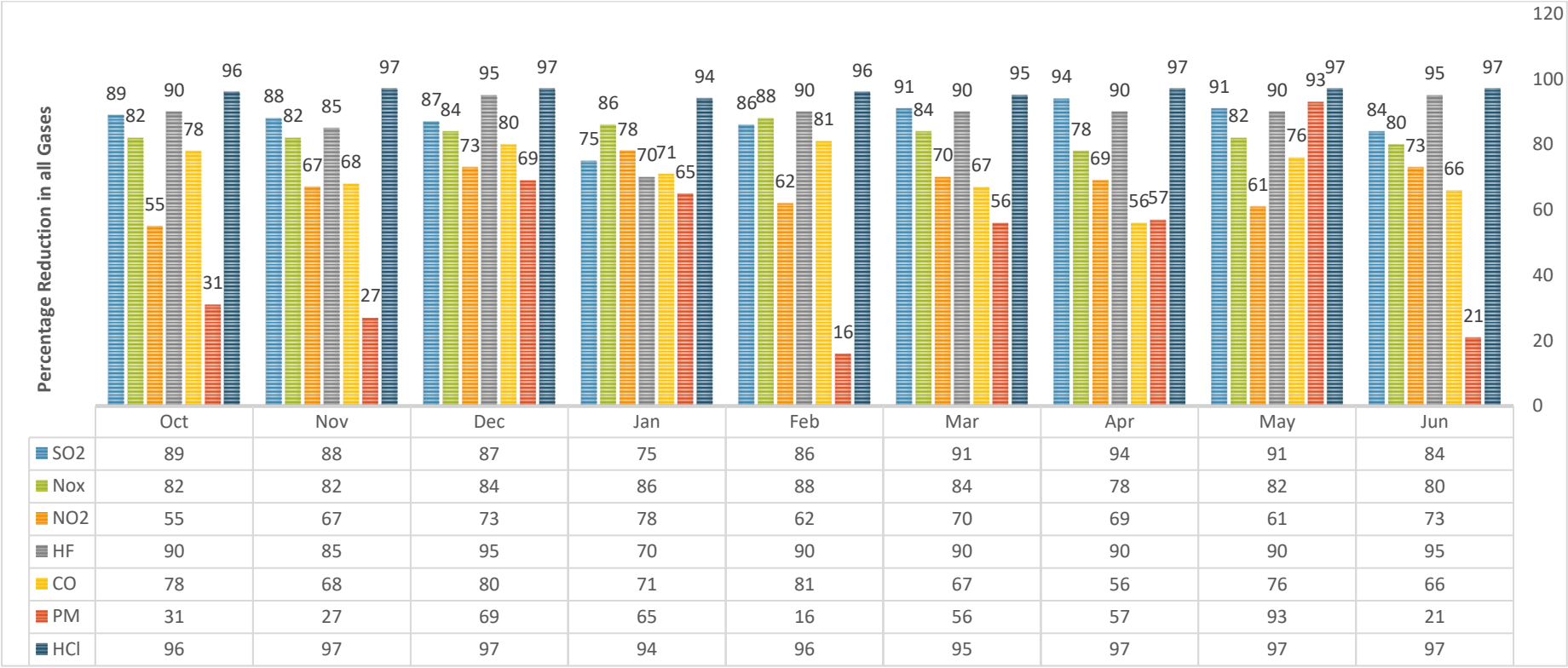


Figure 4.7: Carbon monoxide percentage reduction after the use of hydrated lime

It was found that the $Ca(OH)_2$ injections have an influence on CO reduction however the reduction of CO emissions were linked with high temperature intervals in the furnace. CO are unburned gaseous combustibles that are emitted from the incineration process. It was noted that during startups, furnace upsets, poking or other conditions preventing complete combustion, unburned combustible emissions increased significantly. It was also found that the treatment of waste with high moisture content, such as anatomical waste, had a great influence on generating the amount of CO measured. The average CO recorded was 74%.

4.4.7 Reduction of All Gases in Percentage

Figure 4.8 shows an overall reduction at a glance view of different gases in percentages. SO_2 had an average reduction of 87%, NO_x had average reduction of 83%, NO_2 had an average reduction of 74%, HF had an average reduction of 86%, PM had an average increase of 31%, and HCl had an average reduction of 97%. The highest reduction achieved was 97% HCl and the highest increase was 31% for PM.



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
SO2	89	88	87	75	86	91	94	91	84
Nox	82	82	84	86	88	84	78	82	80
NO2	55	67	73	78	62	70	69	61	73
HF	90	85	95	70	90	90	90	90	95
CO	78	68	80	71	81	67	56	76	66
PM	31	27	69	65	16	56	57	93	21
HCl	96	97	97	94	96	95	97	97	97

Figure 4.8: An overall at a glance view of reduction for different acid gases in percentages recorded in 2016/17 sampling period

Figure 4.9 demonstrates the percentage reduction for all different gaseous emissions achieve when hydrated lime was utilised.

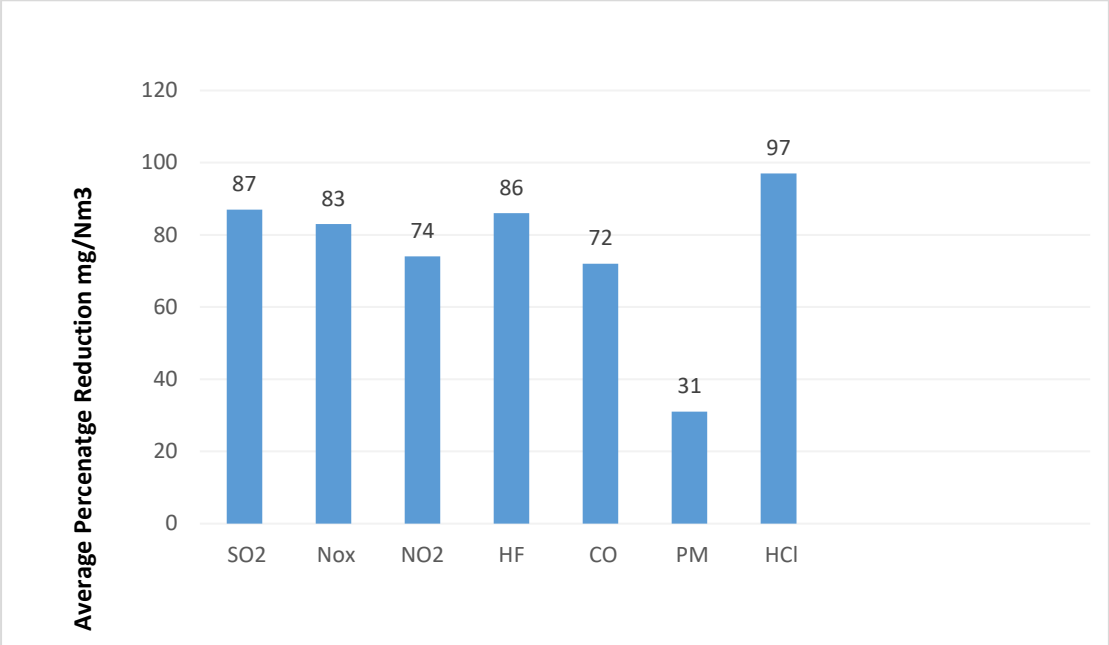


Figure 4.9: Average percentage reduction of different gases between 2014/15 and 2016/17

It was found that HF, NO_x and NO_2 achieved 100% compliance during the course of the study. SO_2 reported a non-compliance in November 2016, June and July 2017. This was due to the competition in flue gas when SO_2 and HCl were treated at the same time. This is agreement with Xinhua (2017) who reported that the injection of hydrated lime into the flue gas for the removal of SO_2, SO_3 and HCl created a competition between gases. Xinhua (2017) recommended that the competition in flue gas be eliminated by injecting sorbent into different locations throughout the flue gas path depending on the operation. Yang *et al.* (2017) agreed that the performance on SO_2 and HCl can vary based on the mixing, injection location and whether the station employed an electrostatic precipitator or fabric filters for their particulate removal device.

HCl also reported non-compliance in January and February 2017, this was due to the same reason as explained in SO_2 non-compliance. It was clearly evident that levels of particulate matter were reportedly high and did not meet the recommended daily limit of 30 mg/Nm^3. CO emissions were reported to have no correlation with $Ca(OH)_2$ injections as they are generated as a product of incomplete combustion; they however

reported a non-compliance in November 2016 due to low temperature intervals. Voicu, Ciobanu, Aura Istrate & Tudor (2020) also reported no correlation between CO emissions and hydrated lime injections but reported high level of particulate matter after injecting the sorbent in two separate locations (before particulate collection device and after the air preheater). In spite of Voicu *et al.* (2020) considering Xinhua (2017) recommendations of injecting lime in different locations to eliminate the competition in different gases, Voicu *et al.* (2020) still reported high amount of particulate matter after using the filtration system.

In a separate study Geng, Wang, Shen & Zhao (2019) injected hydrated lime upstream of the system for the reduction of SO_2, SO_3, HCl and HF prior to interaction with powdered hydrated lime. This allowed an improvement in effectiveness of hydrated lime, the availability of sorbent for all gases treated and the technology proved to be effective in eliminating visible plumes at the stack (Geng *et al.,* 2019). Geng *et al.* (2019) were able to eliminate the competition between gases and also reported less amount of particulate matter.

Vanderreydt (2015) as quoted by Pan, Page, Zhang, Cong, Jonsson, Nasstrom, Destouni, Deal & Kalantari (2019) stated that hydrated lime is typically used for lower SO_2 removal levels of less than 50%. However, Pan *et al.* (2019) enhanced their technology by injecting the sorbent at different location points and achieved a high level reduction of 80% SO_2 when the sorbent was injected prior to a fabric filter and again after the filtration system (Pan *et al.,* 2019). This reported higher injection rates compared when the sorbent was injected downstream at one location point. Pan *et al.* (2019) achieved 90% NO_2, 95% HF and 92% HCl removal efficiency.

Vanderreydt (2015) reported that DSI sorbents did not perform equally when it comes to SO_2 absorption. High levels of SO_3 impeded on hydrated lime performance but naturally occurring halogens in the flue gas were necessary for oxidation and the capturing of HCl (Vanderreydt, 2015). Hydrated lime being more selective towards SO_3 than HCl typically influenced the sorbent performance. Vanderreydt (2015) found that sodium sorbents though more effective on a mass basis were more likely to impede overall HCl removal capabilities thus by creating a competition between HCl and SO_2 emissions.

4.5 Relationship Between $Ca(OH)_2$ Injections and Particulate Matter

Figure 4.10 shows the measurements for particulate matter after the use of hydrated lime injections between 2014/15 before the intervention and 2016/17 after the intervention. Before the intervention, the highest amount for particulate matter was 100 mg/Nm^3 measured in June 2015 and the lowest amount was 65 mg/Nm^3 measured in December 2015. After the intervention, the levels of particulate matter were constantly high throughout the study with the highest amount of 140 mg/Nm^3 in July 2017 and the lowest amount at 105 mg/Nm^3 was measured in October 2016. The peak in January 2017, March 2017, May 2017 and July 2017 were discovered to be as a results of high consumption of lime and also some leakages in the filtration system. The leakages were discovered during the routine maitanance where some of the filters were found either burned or broken. The horizontal red line is the recommended value of 30 mg/Nm^3. Using Wilcoxon signed-rank test the H1 alternative hypothesis was accepted as it was reported that hydrated lime had an impact in increasing the amount of particulate matter and H1 null hypothesis was rejected.

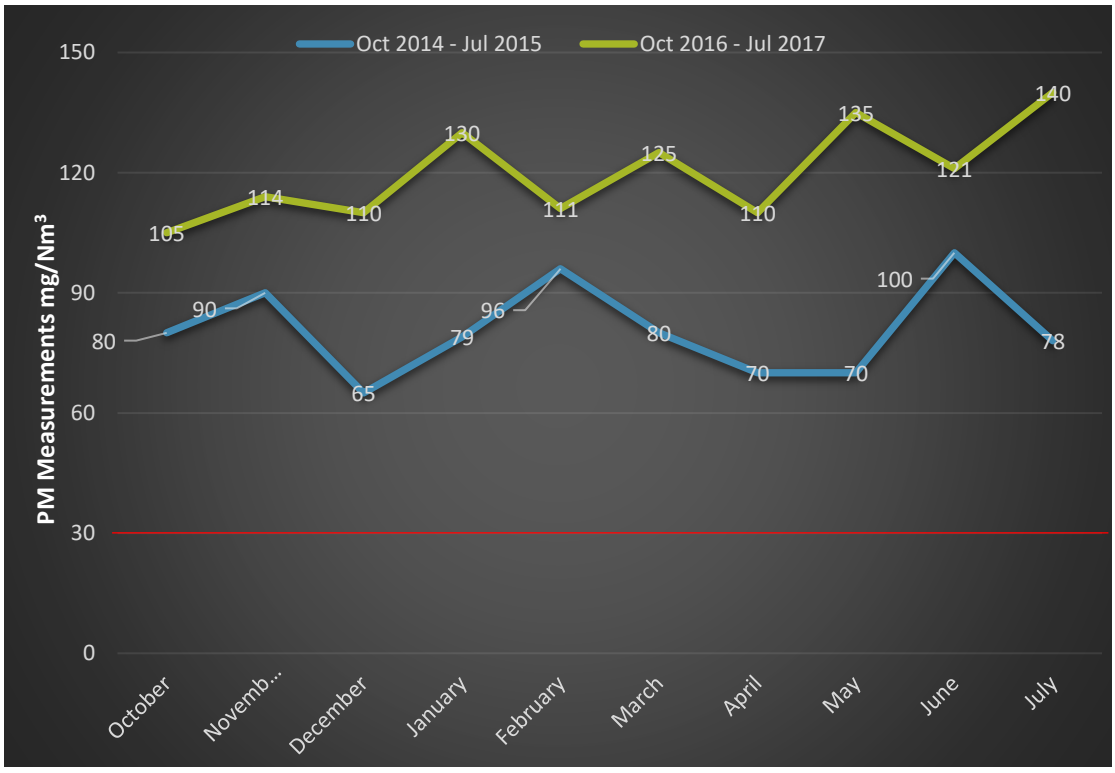


Figure 4.10: Measurements for particulate matter between 2014/15 and 2016/17

The particulate matter is generally referred to as particulates less than 10 mm diameter (PM_{10}). Jones and Allison (2016) in their study found that the amount of particulate matter depended significantly upon the type of the furnace, conditions within the primary chamber, and the components of the materials being treated. In the current study it was found that the utilisation of sodium based sorbents for acid gas removal had an additional effect on the amount of particulate emissions generated. Particulate emissions were highly influenced by the increase of $Ca(OH)_2$ injections, and thus there were potential changes in the collection effectiveness of the PM control device. Since $Ca(OH)_2$ was pneumatically added as a fine powdery form, this had a high influence on the increase of particulate matter.

Figure 4.10 shows the peak of 140 mg/Nm^3 for particulate matter measured in July 2017 after the intervention. The lowest quantity was 105 mg/Nm^3 measured in October 2016. The highest quantity measured in July 2017 was as a result of a high lime dosage of 3.5 kg/h utilised. This was expected as hydrated lime was injected directly into the flue gas adding to the fly ash properties generated in the furnace. The lowest quantity in October 2016 was due to the low sorbent dosage measured at 2.5 kg/h. The findings in Figure 4.10 are in agreement with Vehlow (2015) who stated that the utilization of sorbent material into the incinerator increased the particulate ash in the flue gas system thus increase the need for particulate removal systems.

Particulate matter also increased due to high amount of hydrated lime injections needed for HCl adsorption process. The findings in Figure 4.10 support that the use of $Ca(OH)_2$ to capture acid gas emissions increased the amount of particulate matter released during the treatment of healthcare risk waste. This is because hydrated lime was in powdery form and it was injected directly into the flue gas as dry sorbent injections. More particulate matter was measured during the utilisation of hydrated lime as compared to 2014/15 before the intervention as reflected in Table 4.1.

It is evident that particulate matter is primarily generated during ash removal at the back of the primary chamber, during poking to distribute the heat equally in the chamber, and again during loading. During loading intervals, the guillotine door was opened to receive waste; in the process, more oxygen entered the system resulting in more particulate matter being blown away through the main stack. Although fabric filters were used to capture and control particulate matter, a slight increase was observed as indicated in Figure 4.10.

The statistical analysis in Figure 4.1 indicates that relatively, a complete combustion was highly aligned with residence time, temperature, and turbulence (good air and fuel mixing) and thus minimised particulate emissions (Miller and Miller, 2011). Linear regression graph Figure 4.1f demonstrates that as the residence time increased, particle size and total particulate mass decreased. This was due to HF and other gases that reacted first as the resident time increased, thus required less $Ca(OH)_2$ consumption. It was also found that lower PM emissions were collected at higher temperatures as reflected in Table 4.2 as oxidation rates increased at higher temperatures.

It was found that the entrainment of PM during the incineration process was strongly affected by air velocity within the primary combustion chamber. Linear regression graph in Figure 4.1f indications that due to the low turbulence, the lowest PM emissions were reported. However, incineration facilities require turbulence to achieve full combustion that unfortunately resulted in high PM emissions. About 31% of particulate matter was reported after the utilisation of hydrated lime. Using the secondary data collected in 2014/15 in Table 4.1, Figure 4.9 shows an increase of about 31% in particulate matter.

Xiaowen *et al*. (2015) stated that PM became a principal urban pollutant and considerable amounts of suspended PM were generated after the use of hydrated lime. It was found that the increase in PM was influenced by many factors including removal devices, particle size and resistivity as reflected in a linear regression graph in Figure 4.1f. It was found that the bag filters were able to keep the concentration of PM emissions at a lower level than that of ESP. During the current study, the concentrations of PM were much higher than the limit of 50 mg/Nm^3 required in the recommended standard. For further PM collection to meet the international standard, the corresponding techniques should be applied in this power plant.

The increase in particulate matter poses a potential risk of causing health problems to employees and also to the community. Small particles pose the greatest problems, because they can get deep into the lungs, and some may even get into the bloodstream. Borlace *et al.* (2014) stated that the exposure to such particles can affect both lungs and heart including causing premature death in people with heart or lung disease, non-fatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function and also increased respiratory symptoms, such as irritation of the airways, coughing or difficulty breathing (Borlace *et al.,* 2014).

Albers (2011) studied the impacts of particulate matter on the environment, concluded that particles can be carried over long distances by wind and then settle on ground or water. Depending on their chemical composition, the effects of this settling may include: making lakes and streams acidic, changing the nutrient balance in coastal waters and large river basins, depleting the nutrients in soil, damaging sensitive forests and farm crops, affecting the diversity of ecosystems and contributing to acid rain effects (Albers, 2011).

4.6 Determining the Effectiveness of $Ca(OH)_2$ in Reducing Gaseous Emissions

The effectiveness of $Ca(OH)_2$ in reducing gaseous emissions was determined in two levels: first by comparing the emission findings with air quality standard to determine whether after the use of hydrated lime the emissions were reduced below the recommended limits and secondly by using Wilcoxon signed-rank test. Wilcoxon signed-rank test was performed to compare two samples, 2014/15 emission findings before the use of hydrated lime and 2016/17 emission findings after the use hydrated lime. This was done to determine whether the effectiveness of hydrated lime per each gas was significant or it happened by chance. A comparison sign test analyses was also done in all gases and the results were the same as the Wilcoxon signed-rank test. Using Wilcoxon signed-rank test and sign test, the H1 alternative hypothesis was accepted as there is a significant reduction in all gases except for PM and a null hypothesis was rejected.

4.6.1 Hydrogen Chloride

Table 4.3 demonstrates measurements of hydrogen chloride taken before and after the intervention. Of the peak quantities measured before the intervention, the highest was recorded in April 2015 as 417 mg/Nm^3. The lowest amount measured before the intervention was 223 mg/Nm^3 in March 2015. The highest quantity after the intervention was 15 mg/Nm^3 measured in January 2017 whereas the lowest amount measured was 08 mg/Nm^3 in June 2017. The recommended limit for HCl is 10 mg/Nm^3. In 2016/17 after the intervention HCl was reported above the recommended limit in January 2017, February 2017 and March 2017.

Table 4.3: Comparison of hydrogen chloride findings between 2014/15 and 2016/17

Sampling Period	Temperatures		HCl – 10mg/Nm^3		Difference in mg/Nm^3
	Primary Chamber ^oC	Secondary Chamber ^oC	2014/15 mg/Nm^3	2016/17 mg/Nm^3	
October	900	1160	250	10	240
November	860	1170	300	10	290
December	920	1200	260	9	251
January	860	1000	289	15	274
February	920	1020	315	12	303
March	850	1140	223	11	212
April	880	1190	417	9	408
May	930	1200	328	9	319
June	870	1200	315	8	307
July	850	1200	265	9	256

Table 4.4 below shows the Wilcoxon signed-rank test between 2014/15 HCl emissions and 2016/17 HCl emissions. The p – value of 0.002 for HCl demonstrates that the effectiveness of $Ca(OH)_2$ was significant therefore an alternative hypothesis that hydrated lime is effective in reducing HCl emissions was accepted and a null hypothesis was rejected as 97% reduction was achieved using hydrated lime injections. A sign test was also done for HCl emissions and the results were the same as the Wilcoxon signed-rank test.

Table 4.4: HCl Wilcoxon signed-rank test between 2014/15 and 2016/17 emissions

Variable	Minimum	Maximum	Mean	Std. deviation
HCl 2016/17 mg/Nm^3 after hydrated lime treatment	8.000	15.000	10.200	2.044
HCl 2014/15 mg/Nm^3 before hydrated lime treatment	223.000	417.000	296.200	53.907

Wilcoxon signed-rank test / Two-tailed test:	
V	0
Expected value	27.500
Variance (V)	96.250
p-value (Two-tailed)	0.002
alpha	0.05

Liu *et al.* (2012) describe hydrogen chloride (HCl) as an acidic contaminant generated during the incineration of healthcare risk waste. Hydrated lime was utilised as a dry sorbent injection for the capturing of HCl. The ten-minute short residence time encountered stimulated the reduction technique to achieve a high conversion rate. This brought about the high $Ca(OH)_2$ consumption and generated a large number of particulate matter as spent lime (Laird *et al.,* 2012).

The conversion rate for $Ca(OH)_2$ strongly depended on residence time, while the elementary lime conversions were mostly affected by temperature and the reaction with different waste categories. $Ca(OH)_2$ was confirmed as an indispensable sorbent in reducing large amounts of HCl. The initial reaction was restrained by dispensing HCl into the flue gas and the subsequent reaction with gaseous emissions was monitored. The high amount of HCl concentration increased the initial rate of 2.5 kg/h for $Ca(OH)_2$ as well as the conversion rate.

The amount of HCl measured in June 2017 was 8 mg/Nm^3 and the amount of 15 mg/Nm^3 was measured in January 2017 is reflected in Table 4.3. Although the lime consumption rate was 3.0 kg/h in January 2017 and 3.2 kg/h in June 2017, the reduction in January was as a results of additional O_2 in flue gas. The high consumption of hydrated lime was required for excessive reduction of HCl; however, it created blockages on the lime feeder system and reduced the ultimate conversion rate as it was reflected on the maintenance report.

Sorbacal hydrated lime had small particles with diameters of less than 50 µm and the higher surface area stimulated more efficiency in controlling HCl. The reaction took place in a thermos gravimetric analyser at a temperature of 1100°C and 19% O_2 intake.

The reduction of HCl using hydrated lime achieved a significant amount between 90% and 97% as reflected in Table 4.3. Hydrated lime with its large surface area was found to be a better control technology for the removal of HCl. Table 4.2 shows that the most reaction was observed at 1200°C at 3.2 kg/h lime injection and 3000h-1 space velocity. This is similar to Morabito *et al.* (2014) who achieved 97% HCl removal but at the temperature of 900°C.

In their study, Morabito *et al.* (2014) stated that the high efficiency achieved was as a result of the physical properties of the calcined particle, surface area, porosity and pore size distribution. Morabito *et al.* (2014) also emphasized that calcining conditions, such as time and temperature, as well as the type of raw material employed aided in achieving high HCl efficiency. This was found to be in agreement with the findings of the current study where the temperature and resident time were reported to have stimulated the HCl reduction efficiency.

The current study was conducted at a temperature between 850°C and 1200°C with the use of burners with a conductivity of 1 MW and a two-phase combustion system on the primary chamber and secondary chamber. There was an identical heat output in which first the process of gasification in the temperature of 850°C occurred in the primary chamber, and subsequently more heat was added on the secondary chamber reaching the temperature of 1200°C to capture more HCl gases (Table 4.2). The sorbent was found to be effective in removing HCl at high temperature gases as stated by Gupta *et al.* (2016).

The findings in Table 4.2 show that at high temperature, a very fast chemical reaction occurred between hydrated lime and hydrogen chloride and this was observed on the continuous monitoring equipment. This reaction was found to be interconnected to HCl concentration and its mechanism functioning was strongly dependent on moisture content from anatomical waste. It was also observed that the relative humidity had a large effect on the reaction, in the presence of less moisture the reaction increased, and with the low relative humidity, the reaction also increased. Morabito *et al.* (2014) stated that the solids whose structure is less dense prior to calcination normally have a greater sulfurizing capacity. This is in line with the findings of the current study where moisture content from anatomical waste and heavy wet infectious waste were observed to have a great influence on HCl reduction. Morabito *et al.* (2014) concluded that the HCl adsorption efficiency was impeded by water vapour and high concentration of CO_2.

A comparatively high HCl concentration of 1000 ppm, at 1200°C was found to be the optimum temperature for HCl adsorption at 3.2 kg/h convention rate. This contradicts Sarkar and Sarkar (2015) who obtained maximum conversions of 71% for calcium oxide generated, respectively from hydrated lime at a temperature of 850°C and 3100 ppm of HCl. The findings in Figure 4.1g also demonstrate that a $Ca(OH)_2$ feed rate at a varied flow of up to 3.2 kg/h resulted in 97% HCl reduction efficiency. Based on the findings in Table 4.4 it can be concluded that hydrated lime injections were significant in capturing HCl emissions thus the H1 alternative hypothesis accepted and a null hypothesis was rejected.

4.6.2 Hydrogen Fluoride

To determine the effectiveness of hydrated lime in reducing hydrogen fluoride emissions, data was compared before and after the intervention. Table 4.5 shows hydrogen fluoride data collected in 2014/15 before the intervention and in 2016/17 after the intervention. Of the peak quantities measured before the intervention, the highest was 2 mg/Nm^3 recorded in November 2014, December 2014, February 2015 and May 2015. The lowest measurement was 1 mg/Nm^3 measured in October 2014, January 2015, March 2015, and April 2015. The highest amount after the intervention was 0.5 mg/Nm^3 measured in October 2016 and the lowest quantity was 0.1 mg/Nm^3 recorded in January 2017, March 2017, April 2017, and June 2017. The recommended limit for HF is 1 mg/Nm^3 and 2016/17 HF emission findings complied with the air quality standard as seen Table 4.5.

Table 4.5: Comparison of hydrogen fluoride findings between 2014/15 and 2016/17

Sampling Period	**Temperatures**		**HF – 1 mg/Nm^3**		**Difference in mg/Nm^3**
	Primary Chamber ^oC	Secondary Chamber ^oC	2014/15 mg/Nm^3	2016/17 mg/Nm^3	
October	900	1160	1	0.5	0.5
November	860	1170	2	0.3	1.7
December	920	1200	2	0.0	2
January	860	1000	1	0.1	0.9
February	920	1020	2	0.2	1.8
March	850	1140	1	0.1	0.9
April	880	1190	1	0.1	0.9
May	930	1200	2	0.2	1.8
June	870	1200	1.9	0.1	1.8
July	850	1200	1.7	0.2	1.5

Wilcoxon signed-rank test was conducted between 2014/15 HF emissions and 2016/17 HF emissions. The p – value of 0.004 for HF in Table 4.6 below demonstrates that the effectiveness of $Ca(OH)_2$ was significant in reducing HF emissions. The H1 alternative hypothesis that hydrated lime was significant in reducing HF emissions was accepted and a null hypothesis was rejected as 86% reduction was achieved using hydrated lime injections. A sign test was also done for HF emissions and the results were the same as the Wilcoxon signed-rank test.

Table 4.6: HF Wilcoxon signed-rank test between 2014/15 and 2016/17 emissions

Variable	Minimum	Maximum	Mean	Std. deviation
HF 2016/17 mg/Nm^3 after hydrated lime treatment	0.000	1.000	0.100	0.316
HF 2014/15 mg/Nm^3 before hydrated lime treatment	1.000	2.000	1.600	0.516

Wilcoxon signed-rank test / Two-tailed test:	
V	0
V (standardized)	-2.762
Expected value	22.500
Variance (V)	66.375
p-value (Two-tailed)	0.004
alpha	0.05

The uncontrolled HF emissions were approximately 4 ppm before hydrated lime injections; the HF concentration decreased to less than 1 ppm and remained at that very low level throughout the study. Using a percentage analysis formula, it was determined that hydrated lime was able to achieve about 86% reduction of HF. Generally, during the combustion of healthcare risk waste, hydrogen fluoride (HF) is generated from aerosol spray cans that forms part of waste that is not properly segregated from healthcare facilities with the concentration of up to 5 mg/Nm^3. The highest amount after the intervention was 0.5 mg/m^3 recorded during March 2017 and the lowest amount was 0.1 mg/Nm^3 recorded in Jun 2017 and July 2017 (Table 4.5). This was due to low relative humidity at the point of contact, proper segregation of waste at source which aided in the reduction of aerosol spray cans and high gas temperature.

It was found that the reaction of $Ca(OH)_2$ with HF decreased between 900°C and 1060°C as indicated in Table 4.2. The maximum residence time of 15 minutes between hydrated lime and HF was found to have high conversion efficiencies which brought about the low $Ca(OH)_2$ consumption rate. HF reacted more readily with hydrated lime between 1100°C and 1200°C at the consumption rate of 3.0 kg/h. It was found that the efficiency removal for HF relied more on its inceptive low concentration, high temperatures, the stoichiometric ratio and the effectual lime surface area.

Table 4.2 shows that at the high temperature of 1200°C, a strong reaction occurred between $Ca(OH)_2$ and HF. This reaction was found to be a replication and was strongly dependent on the presence of moisture content from waste and the relative humidity.

As stated by Liu *et al.* (2012) when high moisture was present, the reaction of HF was reduced; however, with low relative humidity, the reaction increased as shown in Figure 4.1c. High residence time increased the reactivity and conversions were strongly influenced by high temperatures. It was therefore discovered that the sorbent was found to be more effective in removing HF from high gas temperatures and low $Ca(OH)_2$ consumption rates.

Xiaowen, Lin, Yuxin, Mingming, Xue & Jixin (2015) did not dictate HF gas in their study. They stated that the only acid gases found in flue gas were HCl, SO_2 and NO_x, which were related to the components of the incineration process of healthcare waste. This is in agreement with the findings in Table 4.5, which demonstrate low HF quantities throughout the study due to proper segregation at source and lime dosage usage. Xiaowen *et al.* (2015) however confirmed that acid gases such as SO_2, HCl, and HF when dictated are removed by means of alkaline reagents: dry neutralization with $Ca(OH)_2$, dry neutralization with $NaHCO_3$ and semi-dry neutralization with $Ca(OH)_2$.

In the study Pozzo, Antonioni, Guglielmi, Stramigioli & Cozzani (2016) conducted at a municipality solid waste incinerator; acid gases (HCl, HF, SO_2) were typically reported in the combustion of solid waste with no segregation of aerosol cans. In Pozzo *et al.* (2016), $Ca(OH)_2$ was adopted by several plant operators, in order to guarantee a safety margin for HCl and HF, which was the most critical pollutant in the MSWI context. $Ca(OH)_2$ was used to ensure that the emission concentrations of less abundant acid gases, such as SO_2 and HF under typical process conditions, were also below their emission limits (Pozzo *et al.,* 2016). Based on the findings in Table 4.6 it was concluded that hydrated lime injections were significant in capturing HF emissions thus H1 alternative hypothesis was accepted and a null hypothesis was rejected.

4.6.3 Particulate Matter

Table 4.7 shows particulate matter emissions collected in 2014/15 before the intervention and in 2016/17 after the intervention. Of the peak quantities measured before the intervention, the highest was 100 mg/Nm^3 which was measured in June 2015. The lowest amount measured was 65 mg/Nm^3 in December 2014. The highest monthly average recorded after the intervention was 140 mg/Nm^3 measured in July 2017. The lowest monthly average was 105 mg/Nm^3 measured in October 2016. The recommended limit for PM is 30 mg/Nm^3 and PM were reported above the

recommended limit both before the intervention in 2014/15 and after the intervention in 2016/17.

Table 4.7: Comparison of particulte matter findings between 2014/15 and 2016/17

Sampling Period	Temperatures		PM – 30mg/Nm^3		Difference in mg/Nm^3
	Primary Chamber ^oC	Secondary Chamber ^oC	2014/15 mg/Nm^3	2016/17 mg/Nm^3	
October	900	1160	80	105	-25
November	860	1170	90	114	-24
December	920	1200	65	110	-45
January	860	1000	79	130	-51
February	920	1020	96	111	-15
March	850	1140	80	125	-125
April	880	1190	70	110	-40
May	930	1200	70	135	-65
June	870	1200	100	121	-21
July	850	1200	78	140	-62

Table 4.8 below shows Wilcoxon signed-rank test between 2014/15 PM emissions and 2016/17 PM emissions. The p – value of 0.005 demonstrates that $Ca(OH)_2$ injections were significant in increasing the amount of particulate emissions therefore H1 null hypothesis that hydrated lime has no effect in PM emissions was rejected and an alternative hypothesis was accepted as 31% increase was recorded after the using hydrated lime injections. A sign test was also done for PM emissions and the results were the same as the Wilcoxon signed-rank test. There was a significant increase in particulate emissions unlike with other gases where there was a significant decline in emissions.

Table 4.8: PM Wilcoxon signed-rank test between 2014/15 and 2016/17 emissions

Variable	Minimum	Maximum	Mean	Std. deviation
PM 2016/17 mg/Nm^3 after hydrated lime treatment	105.000	140.000	120.100	11.986
PM 2014/15 mg/Nm^3 before hydrated lime treatment	65.000	100.000	80.800	11.448

Wilcoxon signed-rank test / Two-tailed test:	
V	55
V (standardized)	2.805
Expected value	27.500
Variance (V)	96.125
p-value (Two-tailed)	0.005
alpha	0.05

Particulate emissions were reported to have increased during the study as a result of hydrated lime injections (Table 4.7). Using a percentage analysis formula, it was determined that hydrated lime had 31% increase in particulate matter. This increase poses a significant risk to the community, the environment and the employees who are at close proximity of inhaling the particulates. Cozzani (2016) stated that there is no evidence of a safe level of exposure or a threshold below which no adverse health effects occur. The exposure is ubiquitous and involuntary, increasing the significance of this determinant of health. It is estimated that approximately 3% of cardiopulmonary and 5% of lung cancer deaths are attributable to PM globally (Cozzani, 2016).

Cozzani (2016) concluded that mortality rate as a results of PM inhalation is estimated to increase from 0.2 to 0.6% per 10 µg/m^3 of PM_{10}. Since even at relatively low concentrations the burden of air pollution on health is significant, effective management of air quality aiming to achieve the air quality guidelines is necessary to reduce health risks to a minimum. Based on the findings in Table 4.8 it was concluded that hydrated lime injections were significant in increasing the amount of PM emissions thus H1 null hypothesis was accepted and an alternative hypothesis was rejected.

4.6.4 Sulphur Dioxide

Table 4.9 shows SO_2 emissions collected in 2014/15 before the intervention and in 2016/17 after the intervention. The highest quantity recorded before the intervention was 378 mg/Nm^3 measured in May 2015. The lowest quantity was 250 mg/Nm^3 recorded in June 2015. Of the peak quantities measured after the intervention, the highest monthly average was 70 mg/Nm^3 measured in January 2017. The lowest monthly average recorded was 20 mg/Nm^3 measured in April 2017 as reflected in. The recommended limit for SO_2 is 50 mg/Nm^3 and sulphur dioxide emissions were reported above the recommended limit in January 2017 and July 2017.

Table 4.9: Comparison of sulphur dioxide findings between 2014/15 and 2016/17

Sampling Period	**Temperatures**		**SO_2 – 50 mg/Nm^3**		**Difference in mg/Nm^3**
	Primary Chamber ^oC	Secondary Chamber ^oC	2014/15 mg/Nm^3	2016/17 mg/Nm^3	
October	900	1160	350	39	311
November	860	1170	290	35	255
December	920	1200	344	44	300
January	860	1000	285	70	215
February	920	1020	253	36	217
March	850	1140	330	29	301
April	880	1190	337	20	317
May	930	1200	378	33	345
June	870	1200	250	41	209
July	850	1200	350	52	213

Wilcoxon signed-rank test was conducted between 2014/15 SO_2 emissions and 2016/17 SO_2 emissions. The p – value of 0.003 in Table 4.10 demonstrates that the effectiveness of $Ca(OH)_2$ was significant in reducing SO_2 emissions. An alternative hypothesis that hydrated lime was significant in reducing SO_2 emissions was accepted and a H1 null hypothesis was rejected as 87% reduction was achieved using hydrated lime injections. A sign test was also done for SO_2 emissions and the results were the same as the Wilcoxon signed-rank test.

Table 4.10: SO_2 Wilcoxon signed-rank test between 2014/15 and 2016/17 emissions

Variable	Minimum	Maximum	Mean	Std. deviation
SO2 2016/17 mg/Nm^3 after hydrated lime treatment	20.000	70.000	39.900	13.634
SO2 2014/15 mg/Nm^3 before hydrated lime treatment	250.000	378.000	316.700	44.139

Wilcoxon signed-rank test / Two-tailed test:	
V	0
Expected value	27.500
Variance (V)	96.250
p-value (Two-tailed)	0.002
alpha	0.05

Dry scrubbing injection (DSI) was utilised to capture SO_2 through an adsorption method with lower alkaline components. During the study, it was observed that there was a slight competition between HCl in the flue gas and SO_2. HCl formed a consequential adsorption of $Ca(OH)_2$ particles that created a great influence on SO_2 reduction. Table 4.2 shows the highest monthly average of 70 mg/Nm^3 measured in January 2017 at 3.0 kg/h after the intervention and the lowest monthly average of 20 mg/Nm^3 measured in April 2017 at 2.7 kg/h lime dosage. This was due to high gas temperature at the injection point as indicated in Table 4.2.

The ability of hydrated lime to react rapidly with SO_2 at temperatures below 1000°C was recorded. During the current study, it was evident that SO_2 reduction levels were highly dependent on temperatures. Hydrated lime reaction decreased as the temperature declined to approximately 920°C and then increased with the increase in temperature as indicated in Table 4.2. This created significant competition between the removal of HCl and SO_2, thus additional $Ca(OH)_2$ was required as demonstrated in Figure 4.2. The findings in Table 4.9 indicate SO_2 reduction in the convection area as

a dependent element of temperature at which $Ca(OH)_2$ is injected. This is in agreement with the findings in Dowling *et al.* (2015) who concluded that the efficiency of hydrated lime in capturing gaseous emissions increased as the amount of temperature also increased.

Table 4.2 shows that the high efficiency of $Ca(OH)_2$ was achieved at about 1020°C. The findings demonstrate that $Ca(OH)_2$ achieved the excess of 87% SO_2 reduction at an acceptable reagent injection rates of 2.8 kg/h. Linear regression analysis in Figure 4.1a illustrates that the effectiveness of hydrated lime for SO_2 reduction was very much dependent on specific material incinerated at a time such as general infection, anatomical waste and the flue gas properties such as the presence of hydrogen chloride in the flue gas and temperature. The other most critical hydrate characteristic for good SO_2 removal was found to be the surface area utilised for hydrated lime.

The injection of hydrated lime with fine particles thus having large specific surface areas assisted in capturing sulphur dioxide. The findings revealed the principal variables in controlling of sulphur dioxide adsorption using hydrated lime were temperature and moisture contents. It was found that gas flow velocity also played a critical role in adsorption of SO_2: the higher the velocity, the more reaction was observed between SO_2 and $Ca(OH)_2$. Sulphur dioxide application in the flue gas and the relative humidity also determined the amount of SO_2 removal, this is reflected in a statistical analysis in Figure 4.1.

Gupta *et al.* (2016) also found that the, SO_2 removal efficiency was considerably dependent on temperature and $Ca(OH)_2$ injection rate to achieve 100% removal at a temperature of 800°C, with hydrated lime particle diameter of 50µm, a Ca/S molar of 2.5 kg/h, a superficial velocity of 1.0 m/s, and inflow gas concentration of 1000 ppm. However, Dal Pozzo *et al.* (2016) as quoted by Gupta *et al.* (2016) found that the concentration of CO_2 in a range of 0 to 20% volume affected the SO_2 removal efficiency, particularly in the presence of large amounts of solid reagent. However, Gupta *et al.* (2016) concluded that the particle size of the solid reagent exerted a significant influence in the reduction of SO_2.

During the current study, the maximum SO_2 removal was achieved at 1020°C temperature and it required optimisation of both sorbent and process parameters. SO_2 removal efficiencies assessed in the current study reflected enhancements in SO_2 reduction capability with the dry injection process. An average reduction of 87% was achieved; this enabled a close saturation, which enhanced SO_2 removal and lime utilisation as reflected in Table 4.2. SO_2 reduction increased by increasing hydrated

lime injections at high temperatures. Xiaowen, Lin, Yuxin, Mingming, Xue & Jixin (2015) concluded that the suitable temperature for SO_2, HCl, and NO_x reactions ranged between 1000°C and 1200°C and the calcium magnesium acetate (CMA) was added to the system at a temperature above 750°C.

Laird *et al.* (2012) found that SO_2 reduction efficiency utilising hydrated lime injections varied from 75% to 90% at a Ca/S molar ratio of 2.8 kg/h injection rate. Hydrated lime was injected directly into flue gas to capture SO_2 HCl, NO_x, HF and NO_2. As hot flue gas flows onto the top, $Ca(OH)_2$ was injected away from the combustion source where it captured SO_2. The gas concentration then passed through to a fabric filter device to capture the remaining sorbent sodium and spent lime. In contrast to this, Xiaowen *et al*. (2015) found that the reduction of SO_2, HCl, and NO_x was better with the combination of the traditional selective non-catalytic reduction (SNCR) and CMA wet-spray system, instead of $Ca(OH)_2$.

The competition of the $Ca(OH)_2$ to convert SO_2 together with HCl increased as the injection ratio increased (Figure 41a and 4.1g). With more oxygen supplied in the primary chamber, SO_2 reduction also increased. When more gases were treated in the flue gas, more competition was observed as the reactivity of SO_2 and NO_2 increased, HCl slightly decreased because of the competition for alkalinity with the other acid gases as shown in Table 4.2. Using a percentage analysis formula, it was determined that hydrated lime was able to achieve about 87% reduction Figure 4.4. Sorbent injection technologies needed generally low capital costs. The process of hydrated lime sorbents was reliant on temperatures and gas velocity and the process did not require any high maintenance of mechanical equipment. Based on the findings in Table 4.10 it was concluded that hydrated lime injections were significant in capturing SO_2 emissions thus an alternative hypothesis was accepted and a H1 null hypothesis was rejected.

4.6.5 Oxides of Nitrogen

Table 4.11 shows NO_x emissions collected in 2014/15 before the intervention and in 2016/17 after the intervention. The highest quantity recorded before the intervention was 289 mg/Nm^3 measured in February 2015 whereas the lowest amount measured was 180 mg/Nm^3 in April 2015. Of the peak quantities measured after the intervention, the highest was 50 mg/Nm^3 recorded in June 2017. The lowest quantity was 30 mg/Nm^3 measured in January 2017. The recommended limit for NO_x is 200 mg/Nm^3 and NO_x emissions were reported below the recommended limit during 2016/17 period.

Table 4.11: Comparison of oxide of nitrogen findings between 2014/15 and 2016/17

Sampling Period	**Temperatures**		**NO_x – 200 mg/Nm^3**		**Difference in mg/Nm^3**
	Primary Chamber ^oC	Secondary Chamber ^oC	2014/15 mg/Nm^3	2016/17 mg/Nm^3	
October	900	1160	249	44	205
November	860	1170	265	48	217
December	920	1200	244	40	204
January	860	1000	218	30	188
February	920	1020	289	35	254
March	850	1140	280	45	235
April	880	1190	180	39	141
May	930	1200	230	42	188
June	870	1200	250	50	200
July	850	1200	280	37	243

Wilcoxon signed-rank test was conducted between 2014/15 NO_x emissions and 2016/17 NO_x emissions. The p – value of 0.005 in Table 4.12 demonstrates that the effectiveness of $Ca(OH)_2$ was significant in reducing NO_x emissions. A H1 alternative hypothesis that hydrated lime was significant in reducing NO_x emissions was accepted and null hypothesis was rejected as 83% reduction was achieved using hydrated lime injections. A sign test was also done for NO_x emissions and the results were the same as the Wilcoxon signed-rank test.

Table 4.12: NO_x Wilcoxon signed-rank test between 2014/15 and 2016/17 emissions

Variable	Minimum	Maximum	Mean	Std. deviation
NO_x 2016/17 mg/Nm^3 after hydrated lime treatment	30.000	50.000	41.000	6.092
NO_x 2014/15 mg/Nm^3 before hydrated lime treatment	180.000	289.000	248.500	33.140

Wilcoxon signed-rank test / Two-tailed test:	
V	0
V (standardized)	-2.805
Expected value	27.500
Variance (V)	96.125
p-value (Two-tailed)	0.005
alpha	0.05

Hydrated lime was added in the flue gas duct at about 850°C for NO_x capturing and additional SO_2 control. Hydrated lime injections assisted in controlling unwanted NO_2 production. Nitrogen oxide emissions are produced by three chemical compounds generated during combustion: (1) thermal fixation of molecular nitrogen, (2) oxidation of organically bound nitrogen contained in the fuel, and (3) arrangement of NO_x because of the availability of partially oxidised organic species present within the temperature regimes. These three distinctive reaction processes are generally referred to as heat, fuel and oxygen.

The findings in Table 4.11 show the peak of 50 mg/Nm^3 after the intervention and the lowest monthly average was 30 mg/Nm^3 measured in January 2017. O_2 was found to be an important element for NO_x reduction in January 2017. NO_x reduction increased with increasing SO_2 concentration (Figure 4.1b). SO_2 was not required to obtain an additional NO_x reduction; only the reaction of $Ca(OH)_2$ in the reagent was required to achieve NO_x reduction. SO_2 reduction was relatively not affected by NO_x.

Linear regression analysis in Figure 4.1a and 4.1b shows that the increasing concentration of O_2 improved SO_2 and NO_x reduction. At a high O_2 concentration of 15%, little NO_x removal was achieved (Table 4.2). The findings in Figure 4.2 reflect that with common purity nitrogen and 15% O_2, NO_x removal was 83%. With an additional 2% O_2, NO_x removal improved up to 87%. These findings show that gas and solid phase oxidation of NO played a role in NO_x reduction. The analysis of the product gas for NO_2 was inconclusive, presumably because of reactions in the gas sampling system. In their study, Morocco and Mora (2012) used a small scale tests and achieved 87% SO_2 removal, and overall NO_x removals of up to 83% for the process when combined with low NO_x burners.

Steel and Patrick (2011) achieved 88% NO_x reduction at lower operating temperatures between 920°C and 1020°C. In the current study, the increase of $Ca(OH)_2$ to 2.8 kg/h increased the NO_x reduction and decreased the lime required for SO_2 control. NO_x removal of up to 88% was achieved at 2.8 kg/h as reflected in Figure 4.1b. Reduction of NO_x also relied mostly on the SO_2 and NO ratio in the flue gas. It ought to be noted that the temperatures required to advance NO_x reduction also suppressed the SO_2 reduction, making it challenging to concurrently achieve both NO_x and SO_2 reduction.

In Morocco and Mora (2012), the gas entering the FGD unit was previously treated in a NO_x removal unit. They found that the presence of CO_2, O_2, and NO_x with SO_2 in the gas phase at their typical concentrations in the flue gas had slight effects on the adsorption of hydrated lime if O_2 and NO_x were not present together. Dry scrubbing injection (DSI) was used to remove NO_x through an adsorption process with alkaline particles, as for example hydrated lime (Morocco and Mora, 2012).

It must be noted that the reaction of NO_x with $Ca(OH)_2$ happened at an indistinguishable relative rate. No optimum temperature for simultaneous SO_2 and NO_x reduction was established. NO_x reduction increased with the decrease in temperatures while SO_2 removal increased with the increase in temperatures. At 920°C, NO_x reduction was about 1 to 2% slower than SO_2 reduction. At 850°C, NO_x reduction was 2 to 5 times slower than SO_2 reduction, however O_2 improved both SO_2 and NO_x reduction. Using a percentage analysis formula, it was determined that hydrated lime was able to achieve about 83% reduction of NO_x. Based on the findings in Table 4.12 it was concluded that hydrated lime injections were significant in capturing NO_x emissions thus H1 alternative hypothesis was accepted and null hypothesis was rejected.

4.6.6 Nitrogen Dioxide

Table 4.13 shows NO_2 emissions collected in 2014/15 before the intervention and in 2016/17 after the intervention. Of the peak quantities measured before the intervention, the highest was 235 mg/Nm^3 which was recorded in April 2015. The lowest amount measured was 185 mg/Nm^3 in December 2014. The highest monthly average recorded after the intervention was 89 mg/Nm^3 measured in October 2016. The lowest amount was 38 mg/Nm^3 recorded in March 2017 and June 2017. The recommended limit for NO_2 is 200 mg/Nm^3 and NO_2 emissions were reported below the recommended limit during 2016/17 period.

Table 4.13: Comparison of nitric dioxide findings between 2014/15 and 2016/17

Sampling Period	**Temperatures**		**NO_2 – 200 mg/Nm^3**		**Difference in mg/Nm^3**
	Primary Chamber ^oC	Secondary Chamber ^oC	2014/15 mg/Nm^3	2016/17 mg/Nm^3	
October	900	1160	196	89	107
November	860	1170	198	68	130
December	920	1200	185	40	145
January	860	1000	210	47	163
February	920	1020	224	85	139
March	850	1140	218	38	152
April	880	1190	235	72	163
May	930	1200	220	46	134
June	870	1200	190	38	138
July	850	1200	250	39	211

Wilcoxon signed-rank test was conducted between 2014/15 NO_2 emissions and 2016/17 NO_2 emissions. The p – value of 0.005 in Table 4.14 demonstrates that the effectiveness of $Ca(OH)_2$ was significant in reducing NO_2 emissions. An alternative hypothesis that hydrated lime was significant in reducing NO_2 emissions was accepted and a H1 null hypothesis was rejected as 74% reduction was achieved using hydrated lime injections. A sign test was also done for NO_2 emissions and the results were the same as the Wilcoxon signed-rank test.

Table 4.14: NO_2 Wilcoxon signed-rank test between 2014/15 and 2016/17 emissions

Variable	Minimum	Maximum	Mean	Std. deviation
NO_2 2016/17 mg/Nm^3 after hydrated lime treatment	38.000	89.000	56.200	20.286
NO_2 2014/15 mg/Nm^3 before hydrated lime treatment	185.000	250.000	212.600	20.770

Wilcoxon signed-rank test / Two-tailed test:	
V	0
V (standardized)	-2.805
Expected value	27.500
Variance (V)	96.125
p-value (Two-tailed)	0.005
alpha	0.05

It was found that an increase in SO_2 and O_2 enormously intensified the capacity of $Ca(OH)_2$ to capture nitric dioxide. $Ca(OH)_2$ with a large surface area aided in the increase of NO_2 reduction to a maximum rate of 74%. Table 4.13 reflects that the peak after the intervention was 89 mg/Nm^3 measured in October 2016. The lowest quantity was 38 mg/Nm^3 measured in March 2017 and June 2017. The amount of nitric dioxide captured decreased in October 2016 due to the reduction in O_2 content and resident time. The presence of sulphur dioxide and O_2 in the flue gas stream influenced the NO_2 reduction. With SO_2, hydrated lime injections increased the removal efficiency for NO_2.

In the presence of SO_2, NO_2 reduction increased marginally with time. It is concluded that since SO_2 reduction was high, a high concentration of SO_2 in the furnace was gradually generated. More O_2 concentration decreased SO_2 and NO_x conversion. Reduction of NO_2 increased only marginally throughout the course of the study considering that the $Ca(OH)_2$ neutralised the nitrous and nitric acids gathered on the

surface as shown in Figure 4.1d. Even when an additional 3% of O_2 was added on the flue gas stream, it did not improve the reduction rate this was due to low residence time encountered at that time.

Mathieu *et al.* (2012) discovered that more relative humidity aided in the increase of both SO_2 and NO_x reaction. As confirmed by previous researchers studying SO_2 reduction separately, relative humidity had a positive impact on SO_2 reduction (Mathieu *et al.,* 2012). In the current study the increase in NO_x reduction was as a result of more $Ca(OH)_2$ injections added on the furnace to deal with an additional SO_2 as shown in Table 4.2. This impact was as a result of the additional moisture content on the surface from waste calories and the formation of sulphur dioxide components from the reaction of nitrous acid with $Ca(OH)_2$. Great reduction of 74% in NO_2 was achieved when the $Ca(OH)_2$ injection ratio was increased from 2.5 to 3.5 kg/h at 1120°C.

Jones and Harrison (2016) found that hydrated lime or sodium bicarbonate can be used to neutralise acid gases and, in the case of a sodium based sorbent, can also partially reduce NO_2 concentrations. Le Cloirec (2012), as quoted by Jones and Harrison (2016) stated that some facilities used recirculation of the flue gases in the combustion chamber to reduce emissions of NO_2. Le Cloirec (2012) used hydrated lime for the reduction of NO_2 and achieved 90% reduction rate. This reduction of 90% was due to the absence of competition amongst other gases in flue gas; Le Cloirec (2012) only investigated the effectiveness of hydrated lime in capturing NO_2 and particulate matter.

Xiaowen *et al*. (2015) discovered that the maximum fraction of approximately 98% NO_2 reduction was obtained at 700°C, a Ca/S molar ratio of three and a superficial velocity of 0.8 m/s using hydrated lime. In their study, Xiaowen *et al*. (2015) concluded that the increase in average residence time of the gas flow in the reactor explained the increasing NO_2 removal efficiency as a function of the reduction in the superficial velocity of the gas. Xiaowen *et al*. (2015) is also in agreement with the findings of the current study in that low residence time decreased the reduction of NO_2 as reported in October 2016 (Table 4.13). Using a percentage analysis formula, it was determined that hydrated lime was able to achieve about 74% reduction of NO_2. Based on the findings in Table 4.12 it was concluded that hydrated lime injections were significant in capturing NO_2 emissions thus an alternative hypothesis was accepted and a H1 null hypothesis was rejected.

4.6.7 Carbon Monoxide

Table 4.15 shows CO emissions collected in 2014/15 before the intervention and in 2016/17 after the intervention. Of the peak quantities measured after the intervention, the highest was 200 mg/Nm^3 measured in December 2014. The lowest amount was 100 mg/Nm^3 measured in April 2015. The highest monthly average recorded after the intervention was 51 mg/Nm^3 measured in November 2016. The lowest monthly average was 36 mg/Nm^3 measured in February 2017. The recommended limit for CO is 50 mg/Nm^3 and CO emissions were reported above the recommended limit only during November 2016.

Table 4.15: Comparison of carbon monoxide findings between 2014/15 and 2016/17

Sampling Period	**Primary Chamber °C**	**Secondary Chamber °C**	**CO – 50 mg/Nm^3 mg/Nm^3**		**Difference in mg/Nm^3**
			2014/15	**2016/17**	
October	900	1160	186	40	146
November	860	1170	160	51	109
December	920	1200	200	40	160
January	860	1000	154	45	109
February	920	1020	189	36	153
March	850	1140	120	40	80
April	880	1190	100	44	56
May	930	1200	160	39	121
June	870	1200	130	44	86
July	850	1200	150	37	113

Wilcoxon signed-rank test was conducted between 2014/15 CO emissions and 2016/17 CO emissions. The p – value of 0.005 in Table 4.16 demonstrates that the effectiveness of $Ca(OH)_2$ was significant in reducing CO emissions. An alternative hypothesis that hydrated lime was significant in reducing CO emissions was accepted and a H1 null hypothesis was rejected as 72% reduction was achieve using hydrated lime injections and high temperature intervals. A sign test was also done for CO emissions and the results were the same as the Wilcoxon signed-rank test.

Table 4.16: CO Wilcoxon signed-rank test between 2014/15 and 2016/17 emissions

Variable	Minimum	Maximum	Mean	Std. deviation
CO 2016/17 mg/Nm^3 after hydrated lime treatment	36.000	51.000	41.600	4.452
CO 2014/15 mg/Nm^3 before hydrated lime treatment	100.000	200.000	154.900	31.786

Wilcoxon signed-rank test / Two-tailed test:	
V	0
V (standardized)	-2.805
Expected value	27.500
Variance (V)	96.125
p-value (Two-tailed)	0.005
alpha	0.05

Carbon monoxide comes as a result of incomplete combustion. Its formation is a result of inadequate oxygen, insufficient residence time, low temperature and low turbulence (fuel or air mixing) in the combustion chamber. Incomplete combustion of organic components contained in waste material can produce environmental contaminants of different organic components. Table 4.15 reflects the highest amount of 51 mg/Nm^3 after the intervention measured in November 2016. The lowest quantity was 36 mg/Nm^3 measured in February 2017. It was confirmed that the lowest quantity in February 2017 was as a result of high gas temperature and the sufficient oxygen level of 15% (Figure 4.1e).

It was found that there are four fundamental reaction parameters responsible for the release of the gaseous emissions from combustion sources. These are the temperature at which the healthcare risk waste is treated, the resident time given to waste to fully combust, the amount of oxygen supplied at a given time and the amount of friction applied to distribute heat equally inside the primary chamber (Miller and

Miller, 2011). During the incineration of healthcare risk waste, CO was created when either the gas temperature or the oxygen concentration was inadequate to create a complete combustion of CO to CO_2 (Miller and Miller, 2011). Carbon monoxide is an exceptionally steady and hard to oxidise gas. The reaction process was steady at temperatures lower than 1000°C.

Although $Ca(OH)_2$ injections separately do have influence on CO, temperature levels, velocity and turbulence had a great influence in terms of CO concentration. Table 4.2 shows that an increase in temperature decreased CO emissions due to waste material reaching full combustion level. It was found that an increase in velocity and O_2 increased the amount of CO emissions. This is due to gases being rushed out through the stack before they reach their full combustion levels. Because moisture content on healthcare risk waste cannot be confirmed, mass balances could not be pre-determined.

Because of the manual operational system, the level of O_2 varied from one load to the next; this affected the amount of CO tremendously. During the study, the optimum O_2 levels for simultaneous temperature and CO reduction were not established; this is due to the uncertainty of moisture content in different types of waste material, for example nappies, sanitary pads and frozen anatomical waste will have high moisture content compared to surgical gloves, needles and sharps or any general infectious waste. The air flow was also found to be a critical factor in the furnace gas temperature and it affected the CO levels, CO_2 and O_2 emissions. It was found that as the temperatures decreased, this contributed to the increase of carbon to convert CO which increased moisture content slightly.

CO levels vary significantly depending on the waste being treated at a particular time, the temperature maintained and the O_2 level at a time. Based on the findings in Table 4.16 it is therefore concluded that $Ca(OH)_2$ injections had a significant influence on CO levels and combustion conditions thus an alternative hypothesis was accepted and an null hypothesis was rejected. The CO levels were found to be unpredicted and dependent on the type of waste incinerated, amount of O_2, temperature and the resident time given.

Chapter 5: Conclusion

The study was aimed at evaluating the control of stack emissions using hydrated lime injections during incineration of healthcare risk waste. Since the promulgation of the new legislation none of the incinerators in RSA was able to achieve the new air quality standard. The objectives of the study was to find a cost effective method of reducing gaseous emissions to assist incineration facilities, boiler companies, steel and coal manufacturing organisations in meeting the new requirements. These facilities and organisation are required to reduce their stack emission levels by half in 2020. This aim of the study was met as the gaseous emissions from the main stack were evaluated against the air quality recommended daily limits. The aim of this study was delivered through the following objectives:

5.1 Investigate the Optimum Dosage Rate for $Ca(OH)_2$ Required to Reduce Acid Gas Emissions

The literature survey provided essential background information for this study. Currently available, historical and data from this study were used to evaluate the dosage required to reduce acid gas emissions from the stack. It was found that the optimum dosage for SO_2 was 2.7 kg/h, achieving a removal efficiency of 87%. SO_2 was removed by the entrained high surface sorbent in the duct and collected in the particulate removal system. The optimum dosage for NO_x was found to be 2.8 kg/h reaching up to 83% reduction efficiency. It is concluded that a high O_2 level of 19% improved SO_2 and NO_x reduction respectively.

The optimum dosage for NO_2 was found to be 3.2 kg/h attaining an average reduction of 74% efficiency. This was due to the presence of sulphur dioxide and O_2 in the flue gas stream that influenced the NO_2 reduction. The reduction of NO_2 decreased marginally throughout the course of the study due to the competition in flue gas duct.

The optimum dosage for HF was found to be 3.0 kg/h achieving the removal efficiency of 86%. This high reduction was due to the low presence of moisture content from the waste treated and the low relative humidity. However, the high residence time aided in the increase of HF reaction. The optimum dosage for HCl was found to be 3.2 kg/h attaining an average reduction of 97% efficiency. It was concluded that the utilisation

of sodium sorbent at high temperatures increased the HCl reduction. Using linear regression analysis the alternative hypothesis was accepted as it was found that there was a relationship between lime dosage rate and the reduction of gases and H0 null hypothesis was rejected.

5.2 Evaluate the Degree of Reactivity of $Ca(OH)_2$ with Different Gases at Different Temperatures

HCl was more reactive between 1190°C to 1200°C. It was found that when temperature was increased in the secondary chamber up to 1200°C, more HCl gases were captured. $Ca(OH)_2$ sorbent was found to be effective in removing HCl at high temperature gases. HF was found to be more reactive at 1200°C. It was reported that the reaction of hydrated lime with HF decreased between 900°C and 1060°C. It was concluded that HF reacted more readily with hydrated lime between 1100°C and 1200°C at a consumption rate of 3.0 kg/h.

SO_2 was found to be more reactive at 1020°C. The ability of hydrated lime to react rapidly with SO_2 at temperatures below 1000°C was eminent. During the study it was evident that SO_2 reduction levels were highly dependent on temperature. Hydrated lime reaction decreased as the temperature gradually declined to approximately 920°C. The maximum SO_2 removal was achieved at 1020°C and it required optimisation of both sorbent and process parameters

NO_2 was found to be more reactive between 1120°C and 1200°C. NO_2 reduction increased marginally with the increase in temperature. It was also noted that the amount of NO_2 reduction increased as $Ca(OH)_2$ feed rate increased. NO_x was found to be more reactive at 1020°C. It was found that the lower temperatures between 920°C and 1020°C achieved a high NO_x reduction of 88%. Reduction of NO_x also relied mostly on the SO_2/ NO, ratio, and SO_2 amount in the flue gas. Using linear regression analysis and comparison graphs it was concluded that different gases reacted differently at different temperature intervals.

5.3 Determine the Reduction of Acid Gas Emissions by $Ca(OH)_2$ Injections

An average temperature of 1148°C was maintained during the course of the study and the following average reduction was achieved: the findings in Figure 4.9 support that an average reduction of 97% HCl was achieved, for HF the average reduction of 86% was achieved, for SO_2 the average reduction of 87% was achieved. For NO_2 the average reduction of 74% was achieved, for NO_x the average reduction of 83.3% was achieved. The CO reduction could not be verified as $Ca(OH)_2$ injections have no influence on CO emissions.

5.4 Investigate the Impact and Relationship Between $Ca(OH)_2$ Injections and Particulate Matter

Particulate emissions were highly influenced by the increase of $Ca(OH)_2$ injections. Since $Ca(OH)_2$ was pneumatically added in a fine powdery form, this had a high influence on the increase of particulate matter. It was found that HCl adsorption required high amount of lime injections and increased the amount of particulate matter collected. The use of $Ca(OH)_2$ to capture acid gas emissions increased the amount of particulate matter collected during the treatment of healthcare risk waste. It was found that the increase of lime dosage also had an influence on the amount of particulate matter. This was because hydrated lime comes as a powdery form and it was injected directly into the flue gas as dry sorbent injection. More particulate matter was measured during the utilisation of hydrated lime as compared to 2014/15 before the intervention. Using Wilcoxon signed-rank test H1 alternative hypothesis was accepted as it was reported that hydrated lime had an impact in increasing the amount of particulate matter and a null hypothesis was rejected.

5.5 Evaluate the Effectiveness of $Ca(OH)_2$ in Reducing Acid Gas Stack Emissions in the Incineration of Healthcare Risk Waste

$Ca(OH)_2$ was a successful reagent in capturing of acid gases such as SO_2, NO_2, HCl, NO_x and HF generated during the incineration of healthcare risk waste. It was found that hydrated lime injections did not adversely affect the operation but kept the process in compliance, though towards the higher injection rates. Hydrated lime became a significant portion of the total particulates entering the electrostatic precipitators. Hydrated lime injections were found to be a cost-effective technique for the reduction of gaseous emissions. Combined with this is the fact that the disposal of by-product fly ash does not have financial implications. Expensive hazardous ash disposal was not required as the by-product was taken back to the furnace as a DSI reagent.

The findings clearly demonstrated that hydrated lime was more reactive with all acid gas species at different temperature intervals. Up to 87% of SO_2 removal was achieved during the study. The findings demonstrate that SO_2 reaction was temperature dependent with better removals observed at higher temperatures. For HCl, the findings demonstrate that DSI with hydrated lime obtained full compliance levels of 97%. For HF, the findings demonstrate greater than 86% removal of HF under relatively low feed rates.

Dry scrubbing was found to be more effective in the reduction of acid gas emissions and there was no high capital cost and additional generation of wastewater. Comparably, the semi-dry scrubbing could result into the corrosion of equipment and the clogging of sorbent pipes. Dry scrubbing can be recommended to waste treatment utilities because of its efficiency, easy implementation processes and operational cost efficiency.

The current study has demonstrated that dry sorbent injections is the principle sorbent used to remove acid gases in high temperature applications such as furnace and incinerators. The advantages combined with the ability to effectively and efficiently absorb most pollutants found in flue gas, make hydrated lime the leading choice for DSI. In order to maximize the removal efficiency of all pollutants, it is important to allow the sorbents to remain entrained in the flue gas as long as possible and ensure the sorbent is evenly distributed across the flue duct. This minimizes the excess release of harmful gases into the atmosphere, ambient air, water and soil.

As much as hydrated lime is the best option in controlling emissions, PM must also be considered as this technology is confirmed to increase the amount of particulate matter. This technology will also assist combustion facilities and manufacturing companies in meeting the new environmental standards. This will determine that the type and scale of pollutants emitted by each unit is within permissible limits. That includes protecting the human health against harmful pollutants. To every human on earth, health is wealth; health is paramount for the running of our day to day activities, without which we would have to rely on others to live. Hydrated lime can help protect our health through reduction of harmful pollutants, which is very valuable.

The use of hydrated lime will also prevent economic wastes. With air pollution control, the wastes accrued from dead crops and bad water will be limited or stopped. With the presence of air pollution control, economic slowdowns will be prevented or at least managed to the barest minimum.

The reduction of emissions will also increase worker's productivity and helps to improve the indoor air quality. No matter how strong the immune system is, there are times when it fails, especially when there is excess air pollution. As pollution is controlled, workers can now work for longer period of time and communities and environmental groups will no longer complain about pollution emitted by incinerators.

Over the years, air pollution has become more and more of a problem in SA, which is why scientists and engineers are inventing various methods of controlling air pollutants. Hydrated lime may become one of the preferred technologies in South Africa and other countries. The new air quality requirements can now be met without any struggles or high capital investments or upgrade on the existing facilities. Dry sorbent injections can be used to reduce the stack emissions instead of opting for a more expensive options of overhauling the entire facilities. Hydrated lime has proven to be a most effective and cost effective way of controlling gaseous emissions below the recommended standard. Using Wilcoxon signed-rank test it was found that hydrated lime was significant in reducing gaseous emissions (HCl, HF, NO_x, NO_2, CO and SO_2) below the recommended limits thus the H1 alternative hypothesis was accepted and a null hypothesis was rejected. There was a significant increase in particulate emissions unlike with other gases where there was a significant decline in emissions.

Chapter 6: Recommendations

The study shows that hydrated lime injections were used as an efficient sorbent in reducing gaseous emissions. However, it is recommended that the parameters below be considered during the combustion process to reduce the amount of acid gases generated. Considering the outcome of this study, the following recommendations can be made:

6.1 Oxygen Requirements

Gaseous emissions are generated during the combustion process when combustion air requirements are not met. Combustion air requirements must be considered when reducing the generation of acid gases. To obtain complete combustion of healthcare waste, an adequate amount of oxygen must be provided in the furnace to transform all carbon molecules to CO_2. This amount of oxygen is known as the stoichiometric or conceptual amount. The amount of oxygen required in the combustion phase is established from the chemical equation of waste treated. In the event that a deficient amount of oxygen is provided, an incomplete combustion is created under these conditions and this results in generation of more acid gases. The reduction of air required during combustion decreases the peak flame temperature and generates more acid gas emissions. It is recommended that 12% of O_2 input be maintained during the treatment of healthcare waste to minimise the amount of gases generated in flue gas.

6.2 Temperatures Requirements

The most critical operating parameter required for combustion processes is temperature. As indicated earlier, during the incineration of healthcare waste, temperatures should be maintained between 850°C and 1200°C as per AEL permit conditions. It is recommended that the temperature be closely monitored, especially when loading waste in the furnace as more gases are generated when temperature is low. It is always recommended that both primary and secondary chambers be given enough time to achieve the desired temperatures before waste is loaded. This will ensure that the gas temperatures are adequately maintained. The temperature in the

secondary combustion chamber must first achieve at least 1200°C, and gas residence time must be well established at five seconds per minute; there must be 15% oxygen excess and high turbulence must be encouraged. This mass balance will reduce the amount of gas emissions created.

6.3 Particulate Matter (PM) Control

Particulate control devices such as fabric filters were utilised during the study. It was noted that PM emissions increased as the $Ca(OH)_2$ feeding rate also increased. As much as the fabric filters were utilised, it was observed that a large amount of PM could not be captured. It is recommended that electrostatic precipitators be used instead of fabric filters. Electrostatic precipitators are widely used to trap fine particulate matter in application where a large amount of gas needs treatment. Coal-burning electric generating plants, primary and secondary smelters and incinerators often use electrostatic precipitators in which particles are removed when the dirty gas stream passes across high voltage wires.

6.4 Recommendations for Future Research

Progress has been made in air quality but many important research questions and technical support needs remain. The findings from this research conclude that hydrated lime is a successful reagent in reducing gaseous emissions. It was also noted that the use of hydrated lime caused an increase in particulate matter that created research gaps that need to be explored further. Further research is required to evaluate or suggest improvements on particulate device control measures or explore wet injection sorbent technologies.

Environmental requirements are becoming stricter in terms of dust removal efficiency and emission standards. Further research is required to establish or evaluate different technologies available for dust removal such as the electrostatic precipitators, bag filters, centrifugal sedimentation and wet scrubbing.

References

Acquistapace, C., Marini, A., Corrente, D., 2014. Double filtration: a new design to get outstanding performances. La Termotecnica 2, 57–60 (in Italian).

Al-Awadhi, J.M. & Al-Shuaibi, A.A. (2013). Dust fallout in Kuwait city: Deposition and characterization. Science of the Total Environment, 461–462, 139–148.

Alahmr, F.O.M., Othman, M., Wahid, N.B.A., Halim, A.A. & Latif, M.T. (2012). Compositions of Dust fall around Semi-Urban areas in Malaysia. Aerosol and Air Quality Research, 12, 629- 642.

Albers, P.N. (2011). Baseline assessment of child respiratory health in the highveld priority area. MSc Dissertation. University of Pretoria. Pretoria, South Africa.

Alburto N.J., Ziolkovska, A., Hooper, L., Elliott, P., Cappuccio, F.P. and Meerpohl, J.J. (2013). Effect of lower sodium intake on health: systematic review and meta-analyses. http://www.bmj.com/content/346/bmj.f1326 [Accessed: 10 March 2015].

Anglo American Sustainability report. (2014). Anglo American Position Statement.

Antonioni, G., Sarno, F., Guglielmi, D., Morra, P., Cozzani, V., 2011. Simulation of a two-stage dry process for the removal of acid gases in a MSWI. Chem. Eng. Trans. 24, 1063e1068. http://dx.doi.org/10.3303/CET1124178.

Antonioni, G., Guglielmi, D., Stramigioli, C., Cozzani, V., 2012. MSWI flue gas two stage dry treatment: modeling and simulation. Chem. Eng. Trans. 26, 213e218. http://dx.doi.org/10.3303/CET1226036.

Antonioni, G., Guglielmi, D., Cozzani, V., Stramigioli, C., Corrente, D., 2014. Modelling and simulation of an existing MSWI flue gas two-stage dry treatment. Process Saf. Environ. 92, 242e250. http://dx.doi.org/10.1016/j.psep.2013.02.005.

Antonioni, G., Dal Pozzo, A., Guglielmi, D., Tugnoli, A., Cozzani, V., 2016. Enhanced modelling of heterogeneous gas-solid reactions in acid gas removal dry processes. Chem. Eng. Sci. 148, 140e154. http://dx.doi.org/10.1016/j.ces.2016. 03.009.

Arena, U., 2015. From waste-to-energy to waste-to-resources: the new role of thermal treatments of solid waste in the Recycling Society. Waste Manag. 37, 1e2. http://dx.doi.org/10.1016/j.wasman.2014.12.010.

ARPA, 2011. Environmental Data Yearbook e Emilia Romagna (in Italian). Available at: www.arpa.emr.it/dettaglio_documento.asp?id¼4638&idlivello¼1528 (last accessed: 14/03/2016).

Astrup, T.F., Riber, C., Pedersen, A.J., 2011. Incinerator performance: effects of changes in waste input and furnace operation on air emissions and residues.

Astrup, T.F., Tonini, D., Turconi, R., Boldrin, A., 2015. Life cycle assessment of thermal waste-to-energy technologies: review and recommendations. Waste Manag. 37, 104e115. http://dx.doi.org/10.1016/j.wasman.2014.06.011.

Astrup, T.F., Riber, C., Pedersen, A.J., 2011. Incinerator performance: effects of changes in waste input and furnace operation on air emissions and residues.

Babbie, E.R. & Mouton, J. 2012. The practice of social research. 12th edition. Belmont, CA: Thomson Wadsworth.

Bhattacharya, T., Chakraborty, S., Tuteja, D. & Patel, M. (2013). Zinc and Chromium Load in Road Dust, Suspended Particulate Matter and Foliar Dust Deposits of Anand City, Gujarat. Open Journal of Metal, 3, 42-50.

Baltazar, L.G., Henriques, F.M.A., Jorne, F. and Cidade, M.T. (2014). Combined effect of super plasticiser, silica fume and temperature in the performance of natural hydraulic lime grouts. *Construction Building Material,* 50, 584–597.

Bichisecchi, M., 2014. Design of a Treatment Plant for Residue Salt Solutions from ENEL Power Plants (in Italian). Thesis dissertation. University of Pisa, Italy.

Biganzoli, L., Racanella, G., Rigamonti, L., Marras, R., Grosso, M., 2015. High temperature abatement of acid gases from waste incineration. Part I: Experimental tests in full scale plants. Waste Manage. 36, 98–105. http://dx. doi.org/10.1016/j.wasman.2014.10.021.

Bologa, A., Paur, H.-R., Seifert, H., Woletz, K., Ulbricht, T., 2012. Fine particle generation, evolution and control by small biomass combustion. Manag. Environ. Qual. 23, 36e55.

Borlace, S., Cai, W., Lengaigne, M., Van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M.J., Wu, L. and England, M.H. (2014). Increasing frequency of extreme El Niño events due to greenhouse warming. *Nature Climate Change*, 4(2), 111-116.

Buonanno, G., Scungio, M., Stabile, L., Titler, W., 2012. Ultrafine particle emission from incinerators: the role of the fabric filter. JAWMA 62, 103e111.

Business Day, August 17, 2000. Incinerator shortage blamed for Gauteng's medical

waste buildup.

Charity, M., Shakespear, H. and Lawrence M. (2013). The Effects of Climate Change and Variability on Food Security in Zimbabwe: A Socio-Economic and Political Analysis. *International Journal of Humanities and Social Science,* 3 (6) [Special Issue – March 2013].

Climate and Development Knowledge Network (2012) Managing climate extremes and disasters in Africa: Lessons from the SREX report. CDKN, available online at www.cdkn.org/srex.All correspondence Climate Change http://unfccc.int/files/documentation/text/html/list_search. php? what= &val=&valan=a&anf=0&id=10. Accessed (04/09/2014).

CML, 2016. CML-IA Characterisation Factors. Institute of Environmental Sciences (CML), Universiteit Leiden. Available at: www.universiteitleiden.nl/en/research/ research-output/science/cml-ia-characterisation-factors (last accessed: 14/03/2016).

Constitution of the Republic of South Africa, 1996. https://www.gov.za/documents/constitution/constitution-republic-south-africa-1996-1

Cosscience (2013). People and the Environment: Atmospheric Stability and Air pollution. http://cosscience1.pbworks.com/f/7.03+Temperature+Inversions.pdf [Accessed: 28/05/2013]

Dal Pozzo, A., Antonioni, G., Guglielmi, D., Stramigioli, C., Cozzani, V., 2016. Comparison of alternative flue gas dry treatment technologies in waste-to-energy processes. Waste Manag. 51, 81e90. http://dx.doi.org/10.1016/j.wasman. 2016.02.029.

DEA (Department of Environmental Affairs), 2011, National Climate Change Response White Paper 26 (Oct. 12, 2011), https://www.environment.gov.za/sites/default/files/legislations/national_climate change_response_whitepap er.pdf, *archived at* https://perma.cc/W6WQ-YGZZ.

DEA, (2013). National Environment Management: Air Quality Act, 39 of 2004 (AQA): National Dust Control Regulations. Government Gazette No. 36974. Government Printer, Pretoria, South Africa.

De Veer, C. (2016). Emission Monthly Report compiled by SI Analytics for Biomed Disposal Services.

De Vos, A.S., Strydom, H., Fouché, C.B. & Delport, C.S.L. 2012. Research at grass roots: for the social sciences and human service professions. 4th edition. Pretoria: Van Schaik.

Dowling, A., O'Dwyer, J. and Adley, C.C. (2015). Lime in the limelight.*Journal of Cleaner Production,* 92, 13–22.

Downs, W., Vecci, S. and Warchol, J. (1994). *Incineration of hazardous wastes using closed cycle combustion ash vitrification*. US Patent Available at: https://www.google.com/patents/US5309850 [Accessed May 20, 2016].

EPA, (2012). Standards. http://www.epa.gov/ttn/naaqs/standards/pm/s_pm_index.html. [Accessed: 03/04/2012].

Frank Mitchell, Ben Sparrow, Joshua Zoshi, and Megan Low, 2017. Lowering Cost and Waste in Flue Gas Desulfurization Wastewater Treatment. Business & Technology for the Global Generation Industry

Geng Y., Wang Z., Shen L., Zhao J., 2019. Calculating CO2 emission factor for Chinese cement production based on inorganic carbon and organic carbon. Clean Air Journal 2019.

Guo, W. 2012. A comprehensive assessment of typical municipal solid incineration technologies in China, Res. Environ. Sci. 25 (8) (2012) Chinese.

Goitom H. (2018), *South Africa's Climate Change Commitments and Regulatory Response Potential*, *in* Climate Change: Law and Governance in South Africa 8-1, 8-14 (Tracy-Lynn Humby et al. eds., 1st ed. 2018).

Guglielmi, D., Antonioni, G., Stramigioli, C., Cozzani, V., 2014. Investigation of performance of different sorbents in a two-stage flue gas dry treatment of a MSWI. Chem. Eng. Trans. 36, 187–192. http://dx.doi.org/10.3303/CET1436032.

Harrison, P.A., Berry, P.M. and Paterson, J.S. 2010. Climate change adaptation and mitigation: synergies, antagonisms and trade-offs for biodiversity and ecosystems services. BOU Conference Proceedings – Climate Changeand Birds. [online]. Available from: http://www.bou.org.uk/bouproc-net/ccb/harrison-etal.pdf. (Accessed 4 April 2018).

Hatfield, J.L. and Prueger, J.H. 2015. Temperature extremes: Effect on plant growth and development. Weather and Climate Extremes. 10: 4–10.

Howden. (2013). *Incinerator RD500 manufacturer manual,* 2003.

Ihuah, P.W. and Eaton, D. (2013). The Pragmatic Research Approach: A Framework for Sustainable Management of Public Housing Estates in Nigeria. *Journal of US-China Public Administration*, 10(10), 933–944.

Jadhav, J. P., Kalyani, D. C. Telke, A. A., Phugare, S. S and Govindwar, S. P. (2010). Evaluation of the efficacy of a bacterial consortium for the removal of color, reduction of heavy metals, and toxicity from textile dye effluent. *BioSource Technology,* 101, 165–173.

Jenner, SL. 2013. The transport of pollutants over South Africa and atmospheric sulphur in Cape Town. M.P.h. Thesis, University of Cape Town, Cape Town.

Jiao, F., Cheng, Y., Zhang, L., Yamada, N., Sato, A., Ninomiya, Y., 2011. Effects of HCl, SO2 and H2O in flue gas on the condensation behavior of Pb and Cd vapors in the cooling section of municipal solid waste incineration. Proc. Combust. Inst. 33, 2787e2793.

Jiao, F., Zhang, L., Yamada, N., Sato, A., Ninomiya, Y., 2013. Effect of HCl, SO2 and H2O on the condensation of heavy metal vapors in flue gas cooling section. Fuel Process. Technol. 105, 181e187.

Jones A. M., Harrison R. M. 2016. *Emission of ultrafine particles from the incineration of municipal solid waste: A review.* Division of Environmental Health and Risk Management, School of Geography, Earth and Environmental Sciences, University of Birmingham, United Kingdom.

Kondache, K., Koffi, D., Kayode, J. A., Awokola, S. O. and Adebola, A. 2018. Impact of climate variability on crop yields in Southern Togo. Agricultural Development and Sustainable environment, Nigeria.

Kong, Y. and Davidson H.D. (2010). Dry Sorbent Injection of Sodium Sorbents for SO_2, HCl and Mercury Mitigation. Mercury, 7, 3–6.

Kurukulasuriya, P., Mendelsohn, R., Hassan, R., Benhin, J., Deressa, T., Diop, M., Eid, H.M., Fosu, K.Y., Gbetibouo, G., Jain, S., Mahamadou, A., Mano,R., KabuboMariara, J., El-Marsafawy, S., Molua, E., Ouda, S., Ouedraogo,M., Se´ne,I., Maddison, D., Seo, S.N. and Dinar, A. 2011. Will African Agriculture Survive Climate Change? The World

Bank Economic Review. 20(3):367–388.

Laird, C.P., Smith, K.J. and Looney, B. (2012).Results of dry sorbent injection testing to reduce HCl. In Air and Waste Management Association - Power Plant Air Pollutant Control “MEGA” Symposium 2012, 136–147.

Le Cloirec, P., 2012. Treatments of polluted emissions from incinerator gases: a succinct review. Rev. Environ. Sci. Biotechnol. 11, 381e392.

Linnenluecke, M. K., Griffiths, A. and Winn, M. I. (2013). Firm and industry adaptation to climate change: a review of climate adaptation studies in the business and management field. *Wiley Interdisciplinary Reviews: Climate Change*, 4(5), 397–416.

Liu, G., Shi, L. and Benson, L. (2012). Chemistry modeling of dry sorbent injection for ACID gas removal. In 29th Annual International Pittsburgh Coal Conference 2012, 91–103. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84877627002&partnerID=tZOtx3y1.

Liu, J., Huang, L., Sun, S., Xie, W., 2016. Thermodynamic equilibrium calculations on Cd transformation during sewage sludge incineration. Water Environ. Res. 88 (6), 548e556.

Maponya, P. and Mpandeli, S. (2012). *Climate Change and Agricultural Production in South Africa: Impacts and Adaptation options*.Journal of Agricultural Science.

Margallo, M., Taddei, M.B.M., Hern_andez-Pell_on, A., Aldaco, R., Irabien, A., 2015. Environmental sustainability assessment of the management of municipal solid waste incineration residues: a review of the current situation. Clean. Technol. Environ. Policy 17, 1333e1353. http://dx.doi.org/10.1007/s10098-015-0961-6.

Marocco, L. (2010). Modeling of the fluid dynamics and SO_2 absorption in a gas liquid reactor. *Chemical Engineering Journal*, 162, 217–226.

Marocco, L. and Mora, A. (2013). CFD modeling of the Dry-Sorbent-Injection process for flue gas desulfurization using hydrated lime. *Separation and Purification Technology*, 108, 205–214. Available at:http://www.sciencedirect.com/science/article/pii/S1383586613000993 [Accessed June 20, 2016].

Mathieu, E.L., Finkernagel, F., Murawska, M., Scharfe, M., Jarek, M., Brehm, A. (2012). Recruitment of the ATP-dependent chromatin remodeler dMi-2 to the transcribed region of active heat shock genes. *Nucleic Acids Research,* 40(11), 4879-4891.

McCarthy, T.S. 2011. The impact of acid mine drainage in South Africa. South African Journal of Science.107(5/6): 712-719. doi:10.4102/sajs.v107i5/6.712.

Miller, B.G. and Miller, B.G. (2011). Emissions Control Strategies for Power Plants. In *Clean Coal Engineering Technology*, 375–481.

Moja, S.J. & Mnisi, J.S. (2013). Seasonal variations in airborne heavy metals in Vanderbijlpark, South Africa. Journal of Environmental Chemistry and Ecotoxicology, 5(9), 227-233.

Morabito, E., Contini, D., Belosi, F., Stortini, A.M., Manodori, L. & Gambaro1, A. (2014). Atmospheric Deposition of Inorganic Elements and Organic Compounds at the Inlets of the Venice Lagoon, (2015). Advances in Meteorology. http://dx.doi.org/10.1155/2014/158902 [Accessed: 24/11/2015].

Nalbandian, H. *Trace element emissions from coal*. London: IEA Coal Research; 2012.

Naidoo, S. 2017. Acid Mine Drainage in South Africa, Springer Briefs in Environmental Science, DOI 10.1007/978-3-319-44435-2_2.

News 24,What's causing Cape Town's water crisis?http://www.news24.com/SouthAfrica/News/whats-causing-cape-towns-water-crisis-20170517 (Accessed June 2017).

Norval, M., Lucas, R.M., Cullen, A.P., de Gruijl, F.R., Longstreth, J. and Takizawa, Y. (2011). The human health effects of ozone depletion and interactions with climate change. Photochem Photobiol Sci 2011(10):199-225.

Oosthuizen, M.A., John, J. and Somerset, V. (2010). Mercury exposure in a low income community in South Africa. South Africa Medical Journal 100:366-371

Pan H., Page J., Zhang L., Cong C., Jonsson E., Nasstrom H., Destouni G., Deal B., Kalantari Z., 2019. Understanding interactions between urban development policies and GHG emissions: A case study in Stockholm Region. AMBIO 2019, 1-15

Park, H.W., Choi, S., Park, D.W. (2015). Simultaneous treatment of NO and SO_2 with aqueous $NaClO_2$ solution in a wet scrubber combined with a plasma electrostatic precipitator. *Journal of Hazardous Material*, 285, 117–126.

Parry, M. L., Canziani, O. F., Palutikof, J. P., Van der Linden, P.J and Hanson, C. (2015). *Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge UK: Cambridge University Press.

Patel, C., Lettieri, P., Germanà, A., 2012. Techno-economic performance analysis and environmental impact assessment of small to medium scale SRF combustion plants for energy production in the UK. Process Saf. Environ. Prot. 90, 255–262. http://dx.doi.org/10.1016/j.psep.2011.06.015.

Pozzo, A. D., Antonioni, G., Guglielmi, D., Stramigioli, C. and Cozzani, V. (2016). *Comparison of alternative flue gas dry treatment technologies in waste-to-energy processes.* LISES – Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Alma Mater Studiorum – Università di Bologna.

Quicker, P., Rotheut, M., Noël, Y., Schulten, M., Athmann, U., 2014. Treating WTE flue gases with sodium bicarbonate. Power Mag. 158 (8), 59–63.

Ragazzi, M., Tirler, W., Angelucci, G., Zardi, D., Rada, E.C., 2013. Management of atmospheric pollutants from waste incineration processes: the case of Bozen. Waste Manag. Res. 31, 235e240.

Roes, L., Patel, M.K., Worrell, E., Ludwig, C., 2012. Preliminary evaluation of risks related to waste incineration of polymer nanomaterials. Sci. Total Environ. 417e418, 76e86.

Saner, M. (2012). *Environmental Impact Assessment Report for Biomed Disposal Services*. Geozone Environmental Services.

Sanjeev Manocha and François Ponchon, 2018. Review Management of Lime in Steel,* 1 Carmeuse Group, 1348 Louvain-la-Neuve, Belgium; sanjeev.manocha@carmeuse.com 2 Carmeuse Europe, 1348 Louvain-la-Neuve, Belgium * Correspondence: francois.ponchon@carmeuse.com; Tel.: +32-10-481-694

Sarkar, D.K. and Sarkar, D.K. (2015). Chapter 14 – Air Pollution Control. In *Thermal Power Plant*. pp. 479–522.IEDM Tech. Digest. United Kingdom.

Schantz, M. (2011) Calcium Hydroxide DSI for FBC Boiler Acid Gas Control for – Council of Industrial Boiler Operators;– Lhoist North America; Council of Industrial Boiler Operators (CIBO).

Sewell, M.R. and Dickerman, J. (2012). Dry sorbent injection options for controlling

emissions of HCl and related acid gases. In *Air and Waste Management Association - International Conference on Thermal Treatment Technologies and Hazardous Waste Combustors 2012*. pp. 413–425. Available at: http://www.scopus.com/inward/record.url?eid=2-s2.0-84876034259&partnerID=tZOtx3y1.

Shalaby, AK, Zakey, AS, Tawfik, AB, Solmon, F, Giorgi, F, Stordal, F, Sillman, S, Zaveri, R.A & Steiner, AL. 2012. Implementation and evaluation of online gas-phase chemistry within a regional climate model (RegCM-CHEM4). Geoscientific Model Development 5:149–198.

Siikamäki J (2012) The U.S. Environmental Protection Agency's Acid Rain Program. from http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-Bck-AcidRainProgram.pdf

Special Reliability Scenario Assessment. (2010). Resource Adequacy Impacts of Potential U.S. Environmental Regulations; NERC (North American Electric Reliability Corporation); www.nerc.com; October 2010.

South African Chamber of mines, (2011). *Coal: Key facts and figures*. http://www.chamberofmines.org.za/sa-mining/coal. Accessed (22/6/2016).

South Africa. 2004 National Environmental Management Act: Air Quality Act, No 39 of 2004.

Steel, K.M., and Patrick, J.W. (2011). The production of ultra clean coal by chemical demineralisation. *Fuel*, 80(14), 2019-2023.

The Citizen, May 16 2016. Durban beaches closed as medical waste washes up. https://citizen.co.za/news/south-africa/1120847/durban-beaches-closed-as-medical-waste-washes-up/. [Accessed 25 June 2017]

United Nations Framework Convention on Climate Change. (2011). Implementing Adaptation http: //unfccc.int/adaptation/workstreams/implementing_adaptation/items/2535.php [Accessed 28/09/14].

USEPA, (2012). National Ambient Air Quality Standards (NAAQS). http://www.epa.gov/air/criteria.html [Accessed: 24/11/2015].

Van Caneghem, J., De Greef, J., Block, C., Vandecasteele, C., 2016. NOx reduction in waste incinerators by selective catalytic reduction (SCR) instead of selective non

catalytic reduction (SNCR) compared from a life cycle perspective: a case study. J. Clean. Prod. 112 (5), 4452e4460. http://dx.doi.org/10.1016/j.jclepro.2015. 08.068.

Vanderreydt I. (2015). Inventory of the waste incineration sector in Flanders. Vito, 2001/MIM/R/030.

Vehlow, J., 2015. Air pollution control systems in WtE units - An overview. Waste Management. 37, 58-74.

Voicu G., Ciobanu C., Aura Istrate I., & Tudor P. 2020. Emission Control of Hydrochloric and Fluorhydric Acid in cement factories from Romania. International Journal of Environmental Research and Public Health. Department of Biotechnical System, Faculty of Biotechnical Systems Engineering.

Wojdyga, K., Chorzelski, M., Rozycka-Wronska, E., 2014. Emission of pollutants in flue gases from Polish district heating sources. J. Clean. Prod. 75, 157e165. http://dx.doi.org/10.1016/j.jclepro.2014.03.069.

Xiaowen S., Lin Z., Yuxin X., Mingming S., Xue G.& Jixin S. 2015. *Evaluation of a flue gas cleaning system of a circulating fluidised bed incineration power plant by the analysis of pollutant emissions*. School of Ocean Biology, Shandong University, China.

Xinhua (2017) China finds widespread violations of environmental rules, China.org.cn. Retrieved from http://english.sepa.gov.cn/News_service/media_news/201706/t20170601_415118.shtml [Google Scholar]

Yang C, Cao L, Yang J (2017) Dimensional analysis of an electromembrane reactor for recycling and resource recovery of flue gas desulfurization residuals. Environ Eng Sci 35(2):76–87. 10.1089/ees.2016.0593 [CrossRef] [Google Scholar]

Appendices

Appendix 1: Permission to conduct research study

BIO MED
DISPOSAL SERVICES (PTY) LTD

Bio Med Disposal Services (Pty) Ltd
Reg No: 2000/006335/07

PO Box 6431
Dunswart
1501

13 Lincoln Road
Benoni
1508

Tel: 011 – 8452521
Fax: 011 – 421 8300

725 Greenstone Ridge

Greenstone Hill

1645

27 May 2016

Dear Ms. N.V. Themba

Re: Permission to Conduct Research at Biomed Treatment Services

This serves to confirm that Biomed Disposal Services has granted you permission to conduct your research study using Biomed sampling equipment and other required facilities. You are then requested to share you data, findings and recommendations with management. Biomed management wishes you all the best in your studies.

If there is any further clarity, do not hesitate to contact Biomed management.

Yours sincerely,

P.P.

Dr PD Sekete

Chief Executive Officer

Appendix 2: Ethical clearance letter

UNISA university of south africa

CAES RESEARCH ETHICS REVIEW COMMITTEE

National Health Research Ethics Council Registration no: REC-170616-051

Date: 04/11/2016

Ref #: **2016/CAES/103**
Name of applicant: **Ms NV Sityo**
Student #: **47277076**

Dear Ms Sityo,

Decision: Ethics Approval

Proposal: Control of acid gas stack emissions using sorbacal hydrated lime injections during medical waste incineration: A case study of Biomed incinerator in Benoni

Supervisor: Dr M Togo

Qualification: Postgraduate degree

Thank you for the application for research ethics clearance by the CAES Research Ethics Review Committee for the above mentioned research. Approval is granted for the project.

Please note that the approval is valid for a one year period only. After one year the researcher is required to submit a progress report, upon which the ethics clearance may be renewed for another year.

Due date for progress report: 30 November 2017

The application was reviewed in compliance with the Unisa Policy on Research Ethics by the CAES Research Ethics Review Committee on 03 November 2016.

The proposed research may now commence with the proviso that:

1) *The researcher/s will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.*
2) *Any adverse circumstance arising in the undertaking of the research project that is*

University of South Africa
Preller Street, Muckleneuk Ridge, City of Tshwane
PO Box 392 UNISA 0003 South Africa
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www.unisa.ac.za

relevant to the ethicality of the study, as well as changes in the methodology, should be communicated in writing to the CAES Research Ethics Review Committee. An amended application could be requested if there are substantial changes from the existing proposal, especially if those changes affect any of the study-related risks for the research participants.

3) *The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study.*

Note:

The reference number [top right corner of this communiqué] should be clearly indicated on all forms of communication [e.g. Webmail, E-mail messages, letters] with the intended research participants, as well as with the CAES RERC.

Kind regards,

Signature
CAES RERC Chair: Prof EL Kempen

Signature
CAES Executive Dean: Prof MJ Linington

NB: Conditions

University of South Africa
Preller Street, Muckleneuk Ridge, City of Tshwane
PO Box 392 UNISA 0003 South Africa
Telephone: +27 12 429 3111 Facsimile: +27 12 429 4150
www.unisa.ac.za

Appendix 3: Log book for lime feeder

BIO MED
DISPOSAL SERVICES (PTY) LTD

Bio Med Disposal Services (Pty) Ltd
Reg No: 2000/006335/07

PO Box 6431
Dunswart
1501

13 Lincoln Road
Benoni
1508

Tel: 011-8452521
Fax: 011-421 8300

Lime Log sheet book 2016/17

Date	Time	Shift	Operator	Kg/h	Date	Time	Shift	Operator	Kg/h
01/10/16	06:00	Shift A	Mhungisi	2.5	23/10/16	06:00	Shift B	Elijah	2.5
02/10/16	06:00	Shift A	Mhungisi	2.5	24/10/16	06:00	Shift A	Mhungisi	2.5
03/10/16	06:00	Shift A	Mhungisi	2.5	25/10/16	06:00	Shift A	Mhungisi	2.5
04/10/16	06:00	Shift A	Mhungisi	2.5	26/10/16	06:00	Shift A	Mhungisi	2.5
05/10/16	06:00	Shift A	Mhungisi	2.5	27/10/16	06:00	Shift A	Mhungisi	2.5
06/10/16	06:00	Shift A	Mhungisi	2.5	28/10/16	06:00	Shift A	Mhungisi	2.5
07/10/16	06:00	Shift B	Elijah	2.5	29/10/16	06:00	Shift A	Mhungisi	2.5
08/10/16	06:00	Shift B	Elijah	2.5	30/10/16	06:00	Shift B	Mhungisi	2.5
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11/10/16	06:00	Shift B	Elijah	2.5	03/11/16	06:00	Shift B	Mhungisi	2.6
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23/10/16	06:00	Shift B	Elijah	2.5	15/11/16	06:00	Shift B	Makua	2.6

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29/11/16	06:00	Shift B	Makua	2.6	29/12/16	06:00	Shift B	Makua	3.0
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10/02/17	06:00	Shift A	Elijah	2.8	11/03/17	06:00	Shift A	Elijah	3.2
11/02/17	06:00	Shift A	Elijah	2.8	12/03/17	06:00	Shift B	Thabiso	3.2
12/02/17	06:00	Shift A	Elijah	2.8	13/03/17	06:00	Shift B	Thabiso	3.2

14/03/17	06:00	Shift B	Thabiso	3.2	13/04/17	06:00	Shift A	Elijah	2.7
15/03/17	06:00	Shift B	Thabiso	3.2	14/04/17	06:00	Shift A	Elijah	2.7
16/03/17	06:00	Shift B	Thabiso	3.2	15/04/17	06:00	Shift A	Elijah	2.7
17/03/17	06:00	Shift B	Thabiso	3.2	16/04/17	06:00	Shift A	Elijah	2.7
18/03/17	06:00	Shift A	Elijah	3.2	17/04/17	06:00	Shift A	Elijah	2.7
19/03/17	06:00	Shift A	Elijah	3.2	18/04/17	06:00	Shift B	Thabiso	2.7
20/03/17	06:00	Shift A	Elijah	3.2	19/04/17	06:00	Shift B	Thabiso	2.7
21/03/17	06:00	Shift A	Elijah	3.2	20/04/17	06:00	Shift B	Thabiso	2.7
22/03/17	06:00	Shift A	Elijah	3.2	21/04/17	06:00	Shift B	Thabiso	2.7
23/03/17	06:00	Shift A	Elijah	3.2	22/04/17	06:00	Shift B	Thabiso	2.7
24/03/17	06:00	Shift B	Thabiso	3.2	23/04/17	06:00	Shift B	Thabiso	2.7
25/03/17	06:00	Shift B	Thabiso	3.2	24/04/17	06:00	Shift A	Elijah	2.7
26/03/17	06:00	Shift B	Thabiso	3.2	25/04/17	06:00	Shift A	Elijah	2.7
27/03/17	06:00	Shift B	Thabiso	3.2	26/04/17	06:00	Shift A	Elijah	2.7
28/03/17	06:00	Shift B	Thabiso	3.2	27/04/17	06:00	Shift A	Elijah	2.7
29/03/17	06:00	Shift B	Thabiso	3.2	28/04/17	06:00	Shift A	Elijah	2.7
30/03/17	06:00	Shift A	Elijah	3.2	28/04/17	06:00	Shift A	Elijah	2.7
01/04/17	06:00	Shift A	Elijah	2.7	30/04/17	06:00	Shift B	Thabiso	2.7
02/04/17	06:00	Shift A	Elijah	2.7	31/04/17	06:00	Shift B	Thabiso	2.7
03/04/17	06:00	Shift A	Elijah	2.7	01/05/17	06:00	Shift B	Thabiso	3.5
04/04/17	06:00	Shift A	Elijah	2.7	02/05/17	06:00	Shift B	Thabiso	3.5
05/04/17	06:00	Shift A	Elijah	2.7	03/05/17	06:00	Shift B	Thabiso	3.5
06/04/17	06:00	Shift B	Thabiso	2.7	04/05/17	06:00	Shift B	Thabiso	3.5
07/04/17	06:00	Shift B	Thabiso	2.7	05/05/17	06:00	Shift A	Elijah	3.5
08/04/17	06:00	Shift B	Thabiso	2.7	06/05/17	06:00	Shift A	Elijah	3.5
09/04/17	06:00	Shift B	Thabiso	2.7	07/05/17	06:00	Shift A	Elijah	3.5
10/04/17	06:00	Shift B	Thabiso	2.7	08/05/17	06:00	Shift A	Elijah	3.5
11/04/17	06:00	Shift B	Thabiso	2.7	09/05/17	06:00	Shift A	Elijah	3.5
12/04/17	06:00	Shift A	Elijah	2.7	10/05/17	06:00	Shift A	Elijah	3.5

11/05/17	06:00	Shift B	Thabiso	3.5	10/06/17	06:00	Shift B	Makua	3.2
12/05/17	06:00	Shift B	Thabiso	3.5	11/06/17	06:00	Shift A	Mlungisi	3.2
13/05/17	06:00	Shift B	Thabiso	3.5	12/06/17	06:00	Shift A	Mlungisi	3.2
14/05/17	06:00	Shift B	Thabiso	3.5	13/06/17	06:00	Shift A	Mlungisi	3.2
15/05/17	06:00	Shift B	Thabiso	3.5	14/06/17	06:00	Shift A	Mlungisi	3.2
16/05/17	06:00	Shift B	Thabiso	3.5	15/06/17	06:00	Shift A	Mlungisi	3.2
17/05/17	06:00	Shift A	Elijah	3.5	16/06/17	06:00	Shift A	Mlungisi	3.2
18/05/17	06:00	Shift A	Elijah	3.5	17/06/17	06:00	Shift B	Makua	3.2
19/05/17	06:00	Shift A	Elijah	3.5	18/06/17	06:00	Shift B	Makua	3.2
20/05/17	06:00	Shift A	Elijah	3.5	19/06/17	06:00	Shift B	Makua	3.2
21/05/17	06:00	Shift A	Elijah	3.5	20/06/17	06:00	Shift B	Makua	3.2
22/05/17	06:00	Shift A	Elijah	3.5	21/06/17	06:00	Shift B	Makua	3.2
23/05/17	06:00	Shift B	Makua	3.5	22/06/17	06:00	Shift B	Makua	3.2
24/05/17	06:00	Shift B	Makua	3.5	23/06/17	06:00	Shift A	Mlungisi	3.2
25/05/17	06:00	Shift B	Makua	3.5	24/06/17	06:00	Shift A	Mlungisi	3.2
26/05/17	06:00	Shift B	Makua	3.5	25/06/17	06:00	Shift A	Mlungisi	3.2
27/05/17	06:00	Shift B	Makua	3.5	26/06/17	06:00	Shift A	Mlungisi	3.2
28/05/17	06:00	Shift B	Makua	3.5	27/06/17	06:00	Shift A	Mlungisi	3.2
29/05/17	06:00	Shift A	Mlungisi	3.5	28/06/17	06:00	Shift A	Mlungisi	3.2
30/05/17	06:00	Shift A	Mlungisi	3.5	29/06/17	06:00	Shift B	Makua	3.2
01/06/17	06:00	Shift A	Mlungisi	3.2	30/06/17	06:00	Shift B	Makua	3.2
02/06/17	06:00	Shift A	Mlungisi	3.2	31/06/17	06:00	Shift B	Makua	3.2
03/06/17	06:00	Shift A	Mlungisi	3.2	01/07/17	06:00	Shift B	Makua	3.5
04/06/17	06:00	Shift A	Mlungisi	3.2	02/07/17	06:00	Shift B	Makua	3.5
05/06/17	06:00	Shift B	Makua	3.2	03/07/17	06:00	Shift B	Makua	3.5
06/06/17	06:00	Shift B	Makua	3.2	04/07/17	06:00	Shift A	Mlungisi	3.5
07/06/17	06:00	Shift B	Makua	3.2	05/07/17	06:00	Shift A	Mlungisi	3.5
08/06/17	06:00	Shift B	Makua	3.2	06/07/17	06:00	Shift A	Mlungisi	3.5
09/06/17	06:00	Shift B	Makua	3.2	07/07/17	06:00	Shift A	Mlungisi	3.5

08/07/17	06:00	Shift A	Mlungisi	3.5					
09/07/17	06:00	Shift A	Mlungisi	3.5					
10/07/17	06:00	Shift B	Makua	3.5					
11/07/17	06:00	Shift B	Makua	3.5					
12/07/17	06:00	Shift B	Makua	3.5					
13/07/17	06:00	Shift B	Makua	3.5					
14/07/17	06:00	Shift B	Makua	3.5					
15/07/17	06:00	Shift B	Makua	3.5					
16/07/17	06:00	Shift A	Mlungisi	3.5					
17/07/17	06:00	Shift A	Mlungisi	3.5					
18/07/17	06:00	Shift A	Mlungisi	3.5					
19/07/17	06:00	Shift A	Mlungisi	3.5					
20/07/17	06:00	Shift A	Mlungisi	3.5					
21/07/17	06:00	Shift A	Mlungisi	3.5					
22/07/17	06:00	Shift B	Makua	3.5					
23/07/17	06:00	Shift B	Makua	3.5					
24/07/17	06:00	Shift B	Makua	3.5					
25/07/17	06:00	Shift B	Makua	3.5					
26/07/17	06:00	Shift B	Makua	3.5					
27/07/17	06:00	Shift B	Makua	3.5					
28/07/17	06:00	Shift A	Mlungisi	3.5					
29/07/17	06:00	Shift A	Mlungisi	3.5					
30/07/17	06:00	Shift A	Mlungisi	3.5					

Appendix 4: Temperature data

BIO MED
DISPOSAL SERVICES (PTY) LTD

Bio Med Disposal Services (Pty) Ltd
Reg No: 2000/006335/07

PO Box 6431
Dunswart
1501

13 Lincoln Road
Benoni
1508

Tel: 011 – 8452521
Fax: 011 – 421 8300

Temperature Data

October 2016

Date	Primary Chamber °C	Secondary Chamber °C
01/10/16	830	1150
02/10/16	820	1200
03/10/16	840	1140
04/10/16	840	1130
05/10/16	820	1200
06/10/16	830	1150
07/10/16	840	1180
08/10/16	840	1190
09/10/16	820	1170
10/10/16	820	1200
11/10/16	830	1150
12/10/16	830	1180
13/10/16	850	1160
14/10/16	840	1180
15/10/16	820	1190
16/10/16	830	1200
17/10/16	830	1300
18/10/16	840	1190
19/10/16	820	1180

November 2016

Date	Primary Chamber °C	Secondary Chamber °C
01/11/16	840	1160
02/11/16	830	1180
03/11/16	850	1140
04/11/16	820	1130
05/11/16	820	1180
06/11/16	830	1150
07/11/16	830	1180
08/11/16	840	1190
09/11/16	850	1170
10/11/16	850	1180
11/11/16	850	1150
12/11/16	850	1180
13/11/16	850	1160
14/11/16	850	1200
15/11/16	820	1190
16/11/16	830	1200
17/11/16	830	1300
18/11/16	840	1190
19/11/16	830	1180

December 2016

Date	Primary Chamber °C	Secondary Chamber °C
01/12/16	830	1190
02/12/16	840	1150
03/12/16	840	1200
04/12/16	830	1190
05/12/16	820	1170
06/12/16	830	1170
07/12/16	830	1190
08/12/16	820	1180
09/12/16	850	1200
10/12/16	850	1200
11/12/16	850	1150
12/12/16	850	1200
13/12/16	820	1140
14/12/16	840	1130
15/12/16	840	1200
16/12/16	840	1150
17/12/16	830	1180
18/12/16	840	1190
19/12/16	840	1170

20/10/16	820	1190
21/10/16	830	1150
22/10/16	840	1180
23/10/16	840	1190
24/10/16	830	1170
25/10/16	820	1170
26/10/16	830	1190
27/10/16	830	1180
28/10/16	820	1180
29/10/16	820	1190
30/10/16	820	1190
31/10/16	830	1180

20/11/16	820	1190	20/12/16	840	1190
21/11/16	840	1150	21/12/16	840	1190
22/11/16	840	1200	22/12/16	840	1200
23/11/16	840	1190	23/12/16	840	1300
24/11/16	830	1170	24/12/16	830	1190
25/11/16	840	1170	25/12/16	840	1180
26/11/16	840	1190	26/12/16	840	1190
27/11/16	840	1180	27/12/16	840	1150
28/11/16	840	1200	28/12/16	840	1180
29/11/16	840	1200	29/12/16	840	1190
30/11/16	840	1200	30/12/16	840	1190
			31/11/16	840	1200

January 2017

Date	Primary Chamber °C	Secondary Chamber °C
01/01/17	820	1150
02/01/17	840	1150
03/01/17	840	1140
04/01/17	840	1130
05/01/17	830	1180
06/01/17	840	1150
07/01/17	840	1180
08/01/17	840	1190
09/01/17	840	1170
10/01/17	840	1180
11/01/17	820	1190
12/01/17	820	1150

February 2017

Date	Primary Chamber °C	Secondary Chamber °C
01/02/17	840	1160
02/02/17	830	1180
03/02/17	850	1140
04/02/17	820	1130
05/02/17	820	1180
06/02/17	830	1150
07/02/17	830	1180
08/02/17	840	1190
09/02/17	850	1170
10/02/17	850	1180
11/02/17	820	1150
12/02/17	840	1180

March 2017

Date	Primary Chamber °C	Secondary Chamber °C
01/03/17	830	1190
02/03/17	840	1150
03/03/17	840	1200
04/03/17	830	1190
05/03/17	820	1170
06/03/17	830	1190
07/03/17	830	1180
08/03/17	820	1180
09/03/17	850	1190
10/03/17	850	1170
11/03/17	850	1190
12/03/17	850	1180

13/01/17	830	1190
14/01/17	840	1150
15/01/17	840	1200
16/01/17	830	1190
17/01/17	820	1170
18/01/17	830	1170
19/01/17	830	1190
20/01/17	820	1180
21/01/17	820	1200
22/01/17	830	1200
23/01/17	850	1190
24/01/17	820	1200
25/01/17	820	1190
26/01/17	830	1200
27/01/17	830	1300
28/01/17	840	1190
29/01/17	850	1180
30/01/17	820	1190
31/01/17	830	1200

13/02/17	840	1160
14/02/17	840	1200
15/02/17	830	1190
16/02/17	840	1200
17/02/17	840	1300
18/02/17	840	1190
19/02/17	840	1180
20/02/17	840	1190
21/02/17	840	1150
22/02/17	820	1200
23/02/17	830	1190
24/02/17	840	1170
25/02/17	840	1170
26/02/17	830	1190
27/02/17	820	1180
28/02/17	830	1200

13/03/17	820	1140
14/03/17	840	1130
15/03/17	840	1200
16/03/17	840	1150
17/03/17	830	1180
18/03/17	840	1190
19/03/17	840	1170
20/03/17	820	1190
21/03/17	840	1150
22/03/17	840	1200
23/03/17	840	1190
24/03/17	830	1170
25/03/17	840	1170
26/03/17	840	1190
27/03/17	840	1180
28/03/17	840	1200
29/03/17	840	1190
30/03/17	840	1150
31/03/17	840	1190

April 2017

Date	Primary Chamber °C	Secondary Chamber °C
01/04/17	840	1190
02/04/17	830	1180
03/04/17	840	1200
04/04/17	840	1200
05/04/17	840	1190

May 2017

Date	Primary Chamber °C	Secondary Chamber °C
01/05/17	830	1180
02/05/17	840	1140
03/05/17	840	1130
04/05/17	830	1200
05/05/17	820	1150

June 2017

Date	Primary Chamber °C	Secondary Chamber °C
01/06/17	840	1160
02/06/17	840	1200
03/06/17	820	1190
04/06/17	820	1200
05/06/17	830	1300

06/04/17	840	1200		06/05/17	830	1180		06/06/17	830	1190
07/04/17	840	1190		07/05/17	830	1190		07/06/17	850	1180
08/04/17	840	1190		08/05/17	820	1170		08/06/17	840	1190
09/04/17	820	1170		09/05/17	850	1190		09/06/17	840	1150
10/04/17	830	1180		10/05/17	850	1180		10/06/17	840	1200
11/04/17	840	1150		11/05/17	850	1140		11/06/17	820	1190
12/04/17	820	1150		12/05/17	850	1130		12/06/17	820	1170
13/04/17	830	1140		13/05/17	820	1200		13/06/17	830	1160
14/04/17	840	1130		14/05/17	840	1150		14/06/17	830	1200
15/04/17	840	1180		15/05/17	840	1180		15/06/17	850	1190
16/04/17	830	1150		16/05/17	840	1190		16/06/17	840	1200
17/04/17	820	1180		17/05/17	840	1170		17/06/17	840	1300
18/04/17	820	1190		18/05/17	840	1190		18/06/17	840	1190
19/04/17	840	1170		19/05/17	840	1190		19/06/17	820	1180
20/04/17	840	1180		20/05/17	820	1170		20/06/17	820	1190
21/04/17	840	1190		21/05/17	820	1180		21/06/17	830	1150
22/04/17	830	1300		22/05/17	830	1150		22/06/17	830	1200
23/04/17	840	1190		23/05/17	850	1150		23/06/17	850	1190
24/04/17	840	1180		24/05/17	820	1140		24/06/17	840	1170
25/04/17	840	1190		25/05/17	820	1130		25/06/17	840	1160
26/04/17	840	1150		26/05/17	830	1180		26/06/17	840	1200
27/04/17	840	1200		27/05/17	830	1190		27/06/17	820	1190
28/04/17	820	1190		28/05/17	840	1190		28/06/17	820	1200
29/04/17	820	1170		29/05/17	850	1170		29/06/17	830	1300
30/04/17	820	1170		30/05/17	820	1180		30/06/17	830	1190
31/04/17	840	1300						31/06/17	850	1180

July 2017

Date	Primary Chamber °C	Secondary Chamber °C	Date	Primary Chamber °C	Secondary Chamber °C
01/07/17	840	1160	20/07/17	830	1190
02/07/17	830	1180	21/07/17	840	1150
03/07/17	850	1140	22/07/17	840	1200
04/07/17	820	1130	23/07/17	830	1190
05/07/17	820	1200	24/07/17	820	1170
06/07/17	830	1200	25/07/17	830	1170
07/07/17	830	1180	26/07/17	830	1190
08/07/17	840	1190	27/07/17	820	1200
09/07/17	850	1170	28/07/17	850	1200
10/07/17	850	1180	29/07/17	850	1200
11/07/17	850	1150			
12/07/17	850	1180			
13/07/17	850	1160			
14/07/17	850	1200			
15/07/17	820	1190			
16/07/17	830	1200			
17/07/17	830	1300			
18/07/17	840	1200			
19/07/17	830	1200			

Appendix 5: Adjusted daily averages for 2016/17 after the intervention

Adjusted daily averages for the month of October 2016

Date	HCl mg/Nm^3	HF mg/Nm^3	SO_2 mg/Nm^3	NO_x mg/Nm^3	NO_2 mg/Nm^3	PM mg/Nm^3	CO mg/Nm^3
Daily Recommended Limits	10	1	50	200	200	30	50
Monthly Average	10	0.5	44	40	89	105	40
01/10/2016	-	-	-	-	-	-	-
02/10/2016	-	-	-	-	-	-	-
03/10/2016	10	0.5	45	40	88	104	38
04/10/2016	8	0.5	42	39	89	110	39
05/10/2016	9.5	0.5	44	39	89	98	39
06/10/2016	10	0.3	44	39	88	103	38
07/10/2016	10	0.4	43	40	87	103	40
08/10/2016	9	0.4	43	40	86	100	40
09/10/2016	8	0.5	43	40	86	100	40
10/10/2016	9	0.5	44	40	89	105	40
11/10/2016	10	0.5	44	40	89	105	40
12/10/2016	10	0.4	44	39	89	105	39
13/10/2016	9	0.4	43	39	88	105	38
14/10/2016	9	0.4	43	38	88	100	39
15/10/2016	9	0.5	43	39	88	100	38
16/10/2016	10	0.5	42	38	87	98	39
17/10/2016	10	0.5	42	38	87	102	39
18/10/2016	10	0.5	43	39	89	103	39
19/10/2016	10	0.5	43	40	89	105	39
20/10/2016	10	0.5	45	41	89	105	39
21/10/2016	9	0.4	44	40	77	100	40
22/10/2016	9	0.4	44	40	86	106	40
23/10/2016	9	0.4	44	40	86	108	40

24/10/2016	8	0.4	44	39	89	110	38
25/10/2016	8	0.5	43	39	89	103	38
26/10/2016	10	0.5	43	39	88	105	40
27/10/2016	10	0.5	42	40	87	105	40
28/10/2016	10	0.5	44	40	87	105	40
29/10/2016	10	0.5	44	40	89	103	39
30/10/2016	9	0.5	44	39	89	102	39
31/10/2016	10	0.5	44	39	89	105	39

Adjusted daily averages for the month of November 2016

Date	**HCl** mg/Nm^3	**HF** mg/Nm^3	**SO_2** mg/Nm^3	**NO_x** mg/Nm^3	**NO_2** mg/Nm^3	**PM** mg/Nm^3	**CO** mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly Average	10	0.3	70	51	68	114	51
01/11/2016	9	0.3	70	50	68	110	50
02/11/2016	9	0.3	64	50	69	102	50
03/11/2016	10	0.3	69	50	68	104	49
04/11/2016	10	0.4	68	49	69	110	51
05/11/2016	10	0.3	69	49	69	112	51
06/11/2016	10	0.3	64	49	68	113	51
07/11/2016	10	0.4	63	50	67	113	50
08/11/2016	8	04	63	51	66	110	50
09/11/2016	9	0.1	63	51	66	110	50
10/11/2016	9	0.1	70	51	69	115	50
11/11/2016	9	0.2	64	51	69	115	50
12/11/2016	10	0.4	70	51	69	115	51
13/11/2016	10	0.4	66	51	68	115	51
14/11/2016	9	0.4	70	51	68	110	51
15/11/2016	9	0.3	67	50	68	110	50
16/11/2016	9	0.3	69	50	67	113	50
17/11/2016	9	0.3	69	50	67	112	50

18/11/2016	10	0.3	68	51	69	113	50
19/11/2016	10	0.3	70	51	69	115	50
20/11/2016	10	0.3	70	51	69	115	51
21/11/2016	10	0.4	70	50	67	110	50
22/11/2016	10	0.4	70	50	66	116	50
23/11/2016	10	0.4	70	50	66	118	50
24/11/2016	8	0.4	70	49	69	110	51
25/11/2016	9	0.3	67	49	69	113	51
26/11/2016	10	0.3	67	49	68	115	50
27/11/2016	10	0.3	70	50	67	115	50
28/11/2016	9	0.3	70	50	67	115	50
29/11/2016	10	0.3	70	50	69	113	50
30/11/2016	9	0.3	70	50	69	112	50

Adjusted daily averages for the month of December 2016

Date	**HCl** mg/Nm^3	**HF** mg/Nm^3	**SO_2** mg/Nm^3	**NO_x** mg/Nm^3	**NO_2** mg/Nm^3	**PM** mg/Nm^3	**CO** mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly Average	9	0.0	36	40	40	110	40
01/12/2016	9	0.1	30	40	38	110	40
02/12/2016	9	0.0	34	40	40	112	40
03/12/2016	9	0.0	35	40	40	109	39
04/12/2016	9	0.0	33	39	40	110	41
05/12/2016	9	0.0	33	39	40	112	41
06/12/2016	8	0.2	34	39	38	110	41
07/12/2016	8	0.0	33	40	37	113	40
08/12/2016	8	0.0	33	40	36	110	40
09/12/2016	9	0.1	33	40	36	110	40
10/12/2016	9	0.1	30	40	39	110	40
11/12/2016	9	0.2	34	40	39	110	40
12/12/2016	8	0.0	30	40	39	110	40
13/12/2016	8	0.0	36	40	38	110	40
14/12/2016	9	0.0	36	40	38	110	40
15/12/2012	9	0.0	36	40	38	110	40

16/12/2016	9	0.0	36	40	40	109	40
17/12/2016	9	0.0	36	40	40	112	40
18/12/2016	8	0.0	36	40	40	113	40
19/12/2016	8	0.0	36	40	40	115	40
20/12/2016	8	0.0	36	40	40	111	41
21/12/2016	8	0.0	36	40	40	110	40
22/12/2016	8	0.0	30	40	36	110	40
23/12/2016	8	0.0	30	40	36	110	40
24/12/2016	8	0.0	30	39	39	110	41
25/12/2016	9	0.0	37	39	39	108	41
26/12/2016	9	0.0	37	39	40	110	39
27/12/2016	9	0.1	36	39	40	110	39
28/12/2016	9	0.1	36	39	40	110	39
29/12/2016	9	0.1	36	39	40	107	39
30/12/2016	9	0.1	36	39	40	112	39
31/12/2016	9	0.1	36	40	40	111	39

Adjusted daily averages for the month of January 2017

Date	HCl mg/Nm^3	HF mg/Nm^3	SO_2 mg/Nm^3	NO_x mg/Nm^3	NO_2 mg/Nm^3	PM mg/Nm^3	CO mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly average	15	0.1	29	45	47	130	45
01/01/2017	15	0.1	27	45	48	130	45
02/01/2017	15	0.0	27	45	40	132	40
03/01/2017	15	0.0	27	45	40	130	45
04/01/2017	15	0.0	28	45	40	130	44
05/01/2017	15	0.0	29	44	40	132	44
06/01/2017	15	0.2	29	44	47	130	43
07/01/2017	12	0.0	29	44	47	133	45
08/01/2017	12	0.0	29	44	46	130	45
09/01/2017	12	0.1	29	45	46	130	45
10/01/2017	12	0.1	29	45	49	130	45
11/01/2017	12	0.2	29	45	49	130	45

12/01/2017	15	0.1	29	45	49	130	45
13/01/2017	15	0.1	28	45	46	130	45
14/01/2017	15	0.1	28	44	46	130	45
15/01/2017	15	0.1	28	44	46	130	43
16/01/2017	15	0.1	28	44	46	129	43
17/01/2017	15	0.1	28	44	46	129	43
18/01/2017	15	0.1	28	45	46	129	43
19/01/2017	15	0.1	29	45	47	129	45
20/01/2017	15	0.1	29	45	47	129	45
21/01/2017	15	0.0	29	45	47	130	45
22/01/2017	15	0.0	29	45	47	130	45
23/01/2017	16	0.0	29	44	46	130	40
24/01/2017	16	0.0	29	44	49	130	43
25/01/2017	15	0.0	29	44	49	130	43
26/01/2017	15	0.0	29	44	47	130	43
27/01/2017	15	0.1	29	44	47	130	43
28/01/2017	15	0.1	29	44	47	130	45
29/01/2017	15	0.1	29	44	47	130	45
30/01/2017	15	0.1	29	44	47	130	45

Adjusted daily averages for the month of February 2017

Date	**HCl** mg/Nm^3	**HF** mg/Nm^3	**SO_2** mg/Nm^3	**NO_x** mg/Nm^3	**NO_2** mg/Nm^3	**PM** mg/Nm^3	**CO** mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly Average	12	0.2	20	36	85	111	36
01/02/2017	12	0.1	17	35	84	110	35
02/02/2017	12	0.2	17	35	85	112	36
03/02/2017	12	0.2	17	35	85	110	36
04/02/2017	12	0.2	17	35	85	110	36
05/02/2017	12	0.2	20	34	85	112	36
06/02/2017	12	0.2	20	34	85	110	36
07/02/2017	12	0.2	20	34	84	113	35
08/02/2017	12	0.2	20	36	84	110	35
09/02/2017	12	0.1	20	36	84	110	35

10/02/2017	12	0.1	20	36	84	110	35
11/02/2017	12	0.2	20	36	84	110	35
12/02/2017	11	0.1	20	36	84	110	35
13/02/2017	11	0.2	19	36	84	111	36
14/02/2017	11	0.2	19	34	84	111	36
15/02/2017	11	0.2	19	34	83	111	36
16/02/2017	11	0.2	19	34	85	111	36
17/02/2017	11	0.1	19	34	85	111	36
18/02/2017	11	0.1	20	36	85	111	36
19/02/2017	11	0.1	20	36	85	109	34
20/02/2017	12	0.1	20	36	85	109	34
21/02/2017	12	0.2	20	36	85	110	34
22/02/2017	12	0.2	20	36	85	110	34
23/02/2017	12	0.2	20	36	46	110	36
24/02/2017	12	0.2	20	35	49	109	36
25/02/2017	12	0.2	19	35	85	109	36
26/02/2017	12	0.2	19	35	85	109	36
27/02/2017	12	0.1	19	36	85	111	36
28/02/2017	12	0.1	19	36	85	111	36
29/02/2017	12	0.1	19	36	85	111	36

Adjusted daily averages for the month of March 2017

Date	**HCl** mg/Nm^3	**HF** mg/Nm^3	**SO_2** mg/Nm^3	**NO_x** mg/Nm^3	**NO_2** mg/Nm^3	**PM** mg/Nm^3	**CO** mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly Average	11	0.1	33	40	38	125	40
01/03/2017	11	0.1	33	39	37	120	42
02/03/2017	11	0.1	33	40	38	122	42
03/03/2017	11	0.1	33	40	38	125	42
04/03/2017	11	0.1	33	40	38	125	42
05/03/2017	11	0.1	33	40	38	125	42
06/03/2017	10	0.2	30	40	38	122	40
07/03/2017	10	0.2	30	40	37	122	40

08/03/2017	10	0.2	30	39	37	122	40
09/03/2017	10	0.1	30	39	37	122	40
10/03/2017	10	0.1	30	39	37	122	40
11/03/2017	10	0.2	30	39	38	125	40
12/03/2017	11	0.5	30	39	38	125	40
13/03/2017	11	0.1	33	39	38	125	45
14/03/2017	11	0.1	33	40	38	125	43
15/03/2017	11	0.1	33	40	38	125	43
16/03/2017	11	0.1	33	40	38	110	43
17/03/2017	11	0.1	33	40	37	121	43
18/03/2017	11	0.1	33	40	37	121	43
19/03/2017	11	0.1	33	40	37	121	40
20/03/2017	12	0.1	33	40	37	121	40
21/03/2017	11	0.1	33	39	38	121	40
22/03/2017	11	0.1	32	39	38	125	40
23/03/2017	11	0.1	32	39	38	125	40
24/03/2017	10	0.1	32	39	38	125	40
25/03/2017	10	0.1	32	39	38	125	40
26/03/2017	10	0.2	32	40	37	125	40
27/03/2017	10	0.5	32	40	37	125	40
28/03/2017	10	0.1	33	40	37	125	40
29/03/2017	11	0.1	33	40	37	125	40
30/03/2017	11	0.1	33	40	37	125	40

Adjusted daily averages for the month of April 2017

Date	**HCl** mg/Nm^3	**HF** mg/Nm^3	**SO_2** mg/Nm^3	**NO_x** mg/Nm^3	**NO_2** mg/Nm^3	**PM** mg/Nm^3	**CO** mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly Average	9	0.1	41	44	72	110	44
01/04/2017	9	0.1	41	44	72	110	42
02/04/2017	9	0.1	40	43	72	112	42
03/04/2017	9	0.1	40	43	72	110	42
04/04/2017	9	0.1	40	43	72	110	42
05/04/2017	9	0.1	40	43	72	112	42

06/04/2017	9	0.1	40	43	72	110	44
07/04/2017	10	0.1	40	43	72	113	44
08/04/2017	10	0.1	41	44	72	110	44
09/04/2017	10	0.1	41	44	72	110	44
10/04/2017	10	0.1	41	44	72	110	44
11/04/2017	9	0.1	41	44	72	110	44
12/04/2017	9	0.1	41	44	72	110	44
13/04/2017	9	0.1	41	44	72	110	45
14/04/2017	9	0.1	41	43	72	110	43
15/04/2017	9	0.1	41	43	72	110	43
16/04/2017	9	0.1	41	43	72	110	43
17/04/2017	9	0.1	40	43	72	111	43
18/04/2017	11	0.1	40	43	72	111	43
19/04/2017	11	0.1	40	43	72	109	44
20/04/2017	12	0.1	40	43	72	109	44
21/04/2017	11	0.1	40	44	72	110	44
22/04/2017	11	0.1	40	44	72	110	44
23/04/2017	11	0.1	40	44	72	110	44
24/04/2017	9	0.1	41	44	72	109	44
25/04/2017	9	0.1	41	44	72	109	44
26/04/2017	9	0.2	41	44	72	109	44
27/04/2017	9	0.1	41	44	72	110	44
28/04/2017	9	0.1	41	44	72	110	44
29/04/2017	9	0.1	41	44	72	110	44
30/04/2017	9	0.1	41	44	72	110	44

Adjusted daily averages for the month of May 2017

Date	**HCl** (mg/Nm^3)	**HF** (mg/Nm^3)	**SO_2** (mg/Nm^3)	**NO_x** (mg/Nm^3)	**NO_2** (mg/Nm^3)	**PM** mg/Nm^3	**CO** mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly Average	9	0.2	44	39	46	135	39
01/05/2017	9	0.1	41	38	45	140	38

02/05/2017	9	0.1	44	38	46	132	38
03/05/2017	9	0.1	44	38	46	130	38
04/05/2017	9	0.1	44	38	46	130	38
05/05/2017	9	0.1	44	37	46	132	38
06/05/2017	9	0.2	44	37	46	140	38
07/05/2017	8	0.2	44	37	45	133	39
08/05/2017	8	0.2	41	39	45	140	39
09/05/2017	8	0.2	43	39	45	140	39
10/05/2017	8	0.2	42	39	45	140	39
11/05/2017	9	0.2	42	39	44	140	39
12/05/2017	9	0.1	42	39	44	140	39
13/05/2017	9	0.1	44	39	44	130	39
14/05/2017	9	0.1	43	43	44	135	40
15/05/2017	9	0.1	43	38	46	135	40
16/05/2017	9	0.2	43	38	46	135	40
17/05/2017	9	0.2	44	38	46	135	40
18/05/2017	8	0.2	44	38	46	135	39
19/05/2017	8	0.2	44	38	46	135	39
20/05/2017	8	0.2	44	38	46	139	39

21/05/2017	8	0.2	44	39	45	139	39
22/05/2017	8	0.1	44	39	45	139	39
23/05/2017	8	0.1	44	39	45	139	39
24/05/2017	9	0.1	44	39	45	139	37
25/05/2017	9	0.1	43	39	44	139	37
26/05/2017	9	0.2	43	39	44	139	37
27/05/2017	9	0.2	43	37	44	110	37
28/05/2017	9	0.2	44	38	46	130	37
29/05/2017	9	0.2	44	38	46	132	38
30/05/2017	9	0.2	43	39	46	140	38
31/05/2017	9	0.2	43	39	46	110	38

Adjusted daily averages for the month of June 2017

Date	**HCl** mg/Nm^3	**HF** (mg/Nm^3)	**SO_2** (mg/Nm^3)	**NO_x** (mg/Nm^3)	**NO_2** (mg/Nm^3)	**PM** mg/Nm^3	**CO** mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly Average	8	0.1	70	44	38	121	44
01/06/2017	8	0.1	69	45	38	120	44

02/06/2017	8	0.1	69	45	38	112	44
03/06/2017	8	0.1	70	45	36	110	44
04/06/2017	9	0.1	70	45	36	110	44
05/06/2017	9	0.1	70	44	36	112	44
06/06/2017	9	0.2	70	44	36	110	44
07/06/2017	8	0.2	68	44	36	113	45
08/06/2017	8	0.2	68	44	37	120	45
09/06/2017	8	0.0	69	44	37	120	45
10/06/2017	8	0.2	70	43	37	120	45
11/06/2017	9	0.2	70	43	37	120	45
12/06/2017	9	0.1	70	43	38	120	45
13/06/2017	9	0.1	69	43	38	120	43
14/06/2017	9	0.1	69	43	38	125	40
15/06/2017	9	0.1	69	44	38	125	40
16/06/2017	9	0.0	69	38	36	125	40
17/06/2017	9	0.0	69	38	36	125	45
18/06/2017	8	0.1	69	44	36	125	45
19/06/2017	8	0.1	70	44	36	125	45
20/06/2017	8	0.1	70	38	39	129	45

21/06/2017	8	0.2	70	44	39	129	45
22/06/2017	8	0.1	70	44	39	129	39
23/06/2017	8	0.1	68	44	39	129	39
24/06/2017	9	0.1	68	44	39	129	45
25/06/2017	8	0.1	68	44	38	129	45
26/06/2017	8	0.2	70	44	38	129	45
27/06/2017	8	0.1	70	37	38	110	45
28/06/2017	8	0.1	70	38	37	110	45
29/06/2017	8	0.1	68	44	37	112	45
30/06/2017	8	0.2	68	44	37	110	45

Adjusted daily averages for the month of July 2017

Date	HCl (mg/Nm^3)	HF (mg/Nm^3)	SO_2 (mg/Nm^3)	NO_x (mg/Nm^3)	NO_2 (mg/Nm^3)	PM mg/Nm^3	CO mg/Nm^3
Daily Limits	10	1	50	200	200	30	50
Monthly average	9	0.2	52	37	39	140	37
01/07/2017	9	0.2	52	35	38	140	36
02/07/2017	9	0.2	52	37	38	140	34
03/07/2017	9	0.2	50	37	39	140	34

04/07/2017	9	0.2	50	37	39	140	34
05/07/2017	9	0.1	50	35	39	142	34
06/07/2017	9	0.2	50	35	39	140	34
07/07/2017	8	0.2	58	35	36	145	36
08/07/2017	8	0.2	58	35	37	145	36
09/07/2017	8	0.1	58	35	37	145	36
10/07/2017	8	0.2	50	36	37	145	36
11/07/2017	9	0.2	50	36	37	145	37
12/07/2017	9	0.1	50	36	38	120	37
13/07/2017	9	0.1	52	36	38	142	37
14/07/2017	9	0.1	52	36	38	142	37
15/07/2017	9	0.1	52	36	38	142	37
16/07/2017	9	0.2	52	38	39	142	37
17/07/2017	9	0.2	59	36	39	142	40
18/07/2017	10	0.2	59	36	39	135	40
19/07/2017	10	0.2	50	36	39	135	40
20/07/2017	10	0.2	50	38	39	139	40
21/07/2017	10	0.2	50	38	39	139	40
22/07/2017	10	0.1	50	38	39	139	39

23/07/2017	10	0.1	58	38	39	139	39
24/07/2017	9	0.1	58	37	39	129	37
25/07/2017	8	0.1	58	37	38	129	37
26/07/2017	8	0.2	52	37	39	145	37
27/07/2017	8	0.1	52	37	39	145	37
28/07/2017	8	0.1	52	38	39	145	37
29/07/2017	8	0.1	52	36	39	145	36
30/07/2017	8	0.2	52	36	39	139	36
31/07/2017	8	0.2	52	36	39	139	36

Appendix 6: Wilcoxon signed-rank test and sign test between 2014/15 and 2016/17 emissions

PM

Variable	Minimum	Maximum	Mean	Std. deviation
PM 2016/17 mg/Nm3 after hydrated lime treatment	105.000	140.000	120.100	11.986
PM 2014/15 mg/Nm3 before hydrated lime treatment	65.000	100.000	80.800	11.448

Sign test / Two-tailed test:	
N+	10
Expected value	5.000
Variance (N+)	2.500
p-value (Two-tailed)	0.002
alpha	0.05

Test interpretation: As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

Wilcoxon signed-rank test / Two-tailed test:	
V	55
V (standardized)	2.805
Expected value	27.500
Variance (V)	96.125
p-value (Two-tailed)	0.005
alpha	0.05

Test interpretation: As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

Summary (p-values):

Variable\Test	Sign test	Wilcoxon signed-rank test
PM 2016/17 mg/Nm3 after hydrated lime treatment - PM 2014/15 mg/Nm3 before hydrated lime treatment	**0.002**	**0.005**

Source:

CO

Variable	Minimum	Maximum	Mean	Std. deviation
CO 2016/17 mg/Nm3 after hydrated lime treatment	36.000	51.000	41.600	4.452
CO 2014/15 mg/Nm3 before hydrated lime treatment	100.000	200.000	154.900	31.786

Sign test / Two-tailed test:	
N+	0
Expected value	5.000
Variance (N+)	2.500
p-value (Two-tailed)	0.002
alpha	0.05

Test interpretation: As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

Wilcoxon signed-rank test / Two-tailed test:	
V	0
V (standardized)	-2.805
Expected value	27.500
Variance (V)	96.125
p-value (Two-tailed)	0.005
alpha	0.05

Test interpretation: As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

Summary (p-values):

Variable\Test	Sign test	Wilcoxon signed-rank test
CO 2016/17 mg/Nm3 after hydrated lime treatment - CO 2014/15 mg/Nm3 before hydrated lime treatment	**0.002**	**0.005**

Source:

NOx

Variable	Minimum	Maximum	Mean	Std. deviation
NOx 2016/17 mg/Nm3 after hydrated lime treatment	30.000	50.000	41.000	6.092
NOx 2014/15 mg/Nm3 before hydrated lime treatment	180.000	289.000	248.500	33.140

Sign test / Two-tailed test:	
N+	0
Expected value	5.000
Variance (N+)	2.500
p-value (Two-tailed)	0.002
alpha	0.05

Wilcoxon signed-rank test / Two-tailed test:	
V	0
V (standardized)	-2.805
Expected value	27.500
Variance (V)	96.125
p-value (Two-tailed)	0.005
alpha	0.05

Summary (p-values):

Variable\Test	Sign test	Wilcoxon signed-rank test
NOx 2016/17 mg/Nm3 after hydrated lime treatment - NOx 2014/15 mg/Nm3 before hydrated lime treatment	**0.002**	**0.005**

NO2

Variable	Minimum	Maximum	Mean	Std. deviation
NO2 2016/17 mg/Nm3 after hydrated lime treatment	38.000	89.000	56.200	20.286
NO2 2014/15 mg/Nm3 before hydrated lime treatment	185.000	250.000	212.600	20.770

Sign test / Two-tailed test:

N+	0
Expected value	5.000
Variance (N+)	2.500
p-value (Two-tailed)	0.002
alpha	0.05

Wilcoxon signed-rank test / Two-tailed test:

V	0
V (standardized)	-2.805
Expected value	27.500
Variance (V)	96.125
p-value (Two-tailed)	0.005
alpha	0.05

Summary (p-values):

Variable\Test	Sign test	Wilcoxon signed-rank test
NO2 2016/17 mg/Nm3 after hydrated lime treatment - NO2 2014/15 mg/Nm3 before hydrated lime treatment	**0.002**	**0.005**

SO2

Variable	Minimum	Maximum	Mean	Std. deviation
SO2 2016/17 mg/Nm3 after hydrated lime treatment	20.000	70.000	39.900	13.634
SO2 2014/15 mg/Nm3 before hydrated lime treatment	250.000	378.000	316.700	44.139

Sign test / Two-tailed test:

N+	0
Expected value	5.000
Variance (N+)	2.500
p-value (Two-tailed)	0.002
alpha	0.05

Wilcoxon signed-rank test / Two-tailed test:

V	0
Expected value	27.500
Variance (V)	96.250
p-value (Two-tailed)	0.002
alpha	0.05

Summary (p-values):

Variable\Test	Sign test	Wilcoxon signed-rank test
SO2 2016/17 mg/Nm3 after hydrated lime treatment - SO2 2014/15 mg/Nm3 before hydrated lime treatment	**0.002**	**0.002**

HCl

Variable	Minimum	Maximum	Mean	Std. deviation
HCl 2016/17 mg/Nm3 after hydrated lime treatment	8.000	15.000	10.200	2.044
HCl 2014/15 mg/Nm3 before hydrated lime treatment	223.000	417.000	296.200	53.907

Sign test / Two-tailed test:

N+	0
Expected value	5.000
Variance (N+)	2.500
p-value (Two-tailed)	0.002
alpha	0.05

Wilcoxon signed-rank test / Two-tailed test:

V	0
Expected value	27.500
Variance (V)	96.250
p-value (Two-tailed)	0.002
alpha	0.05

Summary (p-values):

Variable\Test	Sign test	Wilcoxon signed-rank test
HCl 2016/17 mg/Nm3 after hydrated lime treatment - HCl 2014/15 mg/Nm3 before hydrated lime treatment	**0.002**	**0.002**

HF

Variable	Minimum	Maximum	Mean	Std. deviation
HF 2016/17 mg/Nm3 after hydrated lime treatment	0.000	1.000	0.100	0.316
HF 2014/15 mg/Nm3 before hydrated lime treatment	1.000	2.000	1.600	0.516

Sign test / Two-tailed test:	
N+	0
Expected value	4.500
Variance (N+)	2.250
p-value (Two-tailed)	0.004
alpha	0.05

Wilcoxon signed-rank test / Two-tailed test:	
V	0
V (standardized)	-2.762
Expected value	22.500
Variance (V)	66.375
p-value (Two-tailed)	0.006
alpha	0.05

Summary (p-values):

Variable\Test	Sign test	Wilcoxon signed-rank test
HF 2016/17 mg/Nm3 after hydrated lime treatment - HF 2014/15 mg/Nm3 before hydrated lime treatment	**0.004**	**0.006**

As the computed p-value is lower than the significance level alpha=0.05, one should reject the null hypothesis H0, and accept the alternative hypothesis Ha.

Appendix 7: Calibration certificate for Procal 2000

APPENDIX A

analytics	*SI Analytics Pty (Ltd) Air Quality Monitoring* *Cems Maintenance sheet*	Date	December 2015
		Doc No	SIA-600-00

Company	Biomed	**Location**	Benoni
Date	14/07/2017	**Time**	08:30
Name	Leo de Veer	**Report/doc No**	bio.2017.07.14

Longitude		**Latitude**		**Altitude**	

Maintenance visit

External	Comment
Shelter	-
Shelter enclosure free of weeds.	yes
Door locks and hinges in order.	yes
Skirting seal in order.	yes

Internal	Comment
Temperature (shelter: 26 - 29°C).	22
Computer/AQWeb logger on.	yes
Air conditioner (a/c) filter clean/ed.	yes
A/c vanes directed towards door.	yes
Brushed out shelter.	yes
Log book signed	
Instrument manuals present.	

Engineer/technician comments/notes

Instrument/s	Gas Analyser – MC3	Supplier	EcoChem Analytics
Serial No	S/N 534		

Initial Operations check

1 Set instrument to standby and allow system to purge. ✓

2 Log instrument readings (Pre). ✓

Item			Expected/set value	MC3				Unit
				Pre		Post		
Main screen		Fraction of full scale of heater (sample cell temperature)	0 - 1	0,45		0,61		n/a
		Fraction of full scale of heater (detector box temperature)	0 - 1	0,50		0,42		n/a
		Barometric pressure	n/a	850,68		850,68		mbar
Main menu	Diagnostics – General status	IR light source	100	100		100		n/a
		Cell temperature	185	185		185		°C
		Detector temperature	55	55		55		°C
		O_2 temperature	635	635		635		°C
		O_2 millivolt	-2.552	2,5		2,4		v
		Flow	n/a	0		.4		l/m
	Diagnostics – Energies		Ref value for measurement	Measured	Abs	Measured	Abs	
		HCL	114,2	160.2	3633	160.2	3633	n/a
		CO	43,8	51.2	41844	51.2	41844	n/a
		SO_2	40,1	24.3	78049	24.3	78049	n/a
		NO	40,1	47.6	-438	47.6	-438	n/a
		NO_2	40,1	15.1	74208	15.1	74208	n/a
		H_2O	114,2	55.1	22876	55.1	22876	n/a
		HF	59,6	76.3	-124	76.3	-124	n/a
	Device data – General data	Date	n/a	14.07.2017		14.07.2017		n/a
		Time	n/a	09.02.41		13.12.11		n/a
	Device data – Critical data – Temp controllers			Kp $*10^{-2}$	Ki $*10^{-6}$	Kp $*10^{-2}$	Ki $*10^{-6}$	
		R1	n/a	0.1	0.002	0,1	0,002	n/a
		R2	n/a	0.1	0.002	0,1	0,002	n/a
		R3	n/a					n/a
Operator functions	Optical Energy	Optical Energy	n/a	26,06		26,06		%

Instrument checks – Shelter

1	Check general condition of equipment for excessive dust, corrosion or physical damage.	✓
2	Check system for leaks/blockages.	✓
3	Check pump for leaks.	✓
4	Ensure pump is giving a flow of between 2-4 l/m.	✓

Instrument checks – Stack

1	Check general condition of equipment for excessive dust, corrosion or physical damage.	✓
2	Check condition of all cables and pipe connections.	✓
3	Clean ceramic filter in probe filter housing.	✓

Calibration checks

1	Active Auto Zero and allow readings to stabilize.	✓
2	Log pre-calibration readings and after zero-calibration log the readings again.	✓
3	Apply highest concentration of test gasses by activating the relevant Span solenoids.	✓
4	Log pre-calibration readings and after calibration log the readings again.	✓

Test gas	HF in N_2	CO in N_2	SO_2 in N_2	NO in N_2
Concentration	10,3 ppm ± 1,6%	169,3 ppm ± 3%	73,8 ppm ± 2,6%	109,3 ppm ± 4,5%
Cylinder pressure	15,0 Mpa	15,0 Mpa	14,0 Mpa	16,0 Mpa
Certificate No	119938	1923195	2014053	1966872
Expiry Date	June 2016	June 2016	June 2016	June 2016

Test gas	NO_2 in N_2	HCL in N_2
Concentration	102,0 ppm ± 4,7%	10,1 ppm 1,6%
Cylinder pressure	16,0 MPa	15,0 Mpa
Certificate No	1966875	5365
Expiry Date	June 2016	November 2016

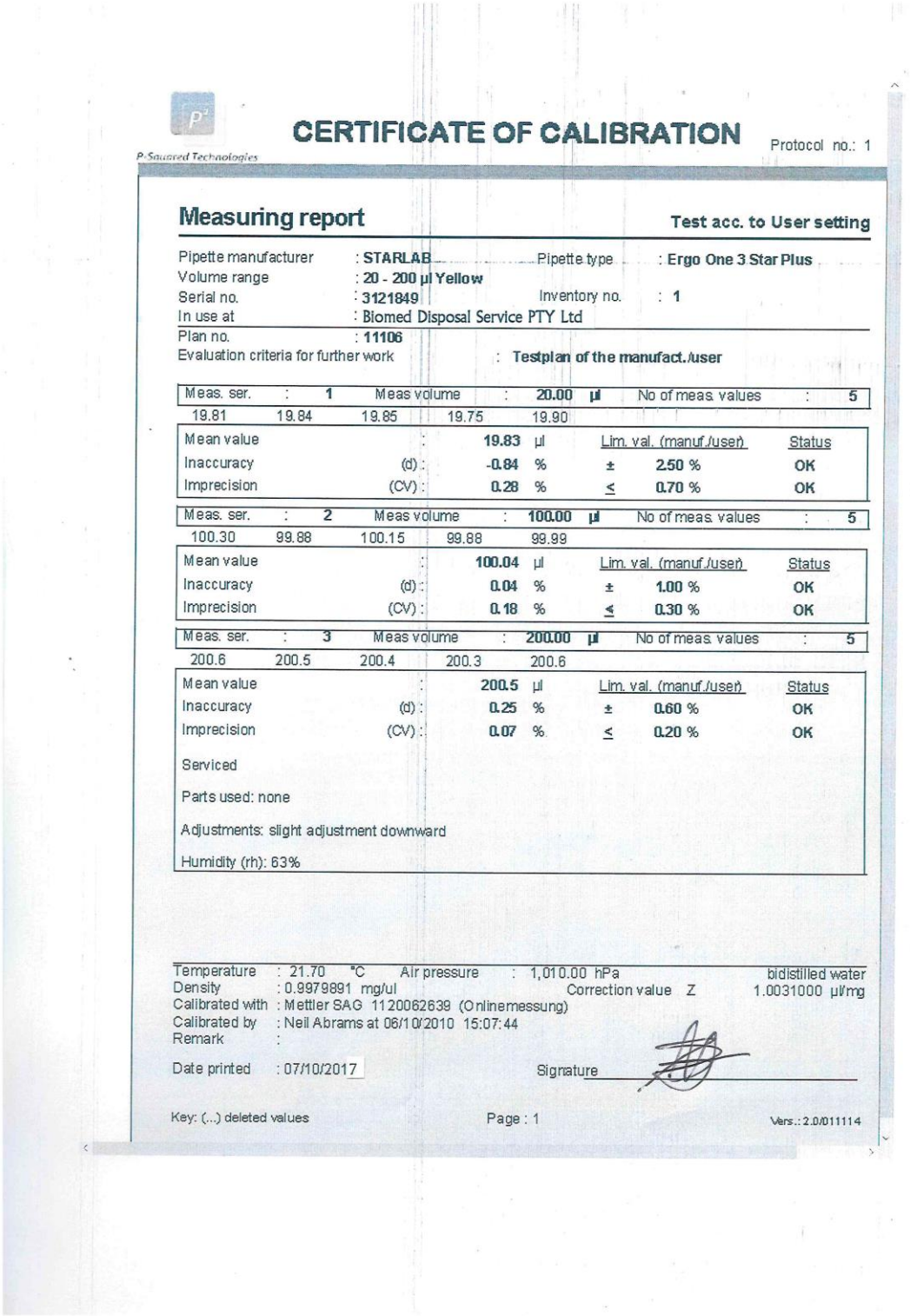
Calibration

Source/Action	Zero calibration			Span calibration		
	Actual	Expected	Calibrated	Actual	Expected	Calibrated
HCl cylinder ppm	0,0	0 mg/m^3	0	98,5	98,42 mg/m3	-
CO cylinder 222 ppm	4,8	0 mg/m^3	0	212,5	211,6 mg/m3	-
SO_2 cylinder 242 ppm	0,5	0 mg/m^3	0	211,7	210,9 mg/m3	-
NO cylinder 99.7 ppm	5,9	0 ppm	0	110	109,3 ppm	-
NO_2 cylinder 98.6 ppm	0,0	0 ppm	0	100	102,0 ppm	-
HF cylinder 9.1 ppm	0,0	0 mg/m3	0	9,0	9,1 mg/m3	-
O_2 21,0%	21,0	20,89 %	21,0		n/a	n/a

Final operations

1	Set instrument to standby and allow system to purge.	✓
2	Log final instrument readings (Post).	✓
3	Place instrument back to measurement mode.	✓
4	Confirm all gas cylinder main valves are properly closed.	✓
5	Confirm that instrument air drier and oil-remover are clean.	✓

Appendix 8: Calibration certificate for temperature logger



P-Sauared Technologies

CERTIFICATE OF CALIBRATION

Protocol no.: 1

Measuring report

Test acc. to User setting

Pipette manufacturer	: **STARLAB**	Pipette type	: **Ergo One 3 Star Plus**
Volume range	: **20 - 200 µl Yellow**		
Serial no.	: **3121849**	Inventory no.	: **1**
In use at	: Biomed Disposal Service PTY Ltd		
Plan no.	: **11106**		
Evaluation criteria for further work		: **Testplan of the manufact./user**	

Meas. ser.	: 1	Meas volume	: 20.00 µl	No of meas. values	: 5
19.81	19.84	19.85	19.75	19.90	

Mean value		:	19.83	µl	Lim. val. (manuf./user)	Status
Inaccuracy	(d) :		-0.84	%	± 2.50 %	OK
Imprecision	(CV) :		0.28	%	≤ 0.70 %	OK

Meas. ser.	: 2	Meas volume	: 100.00 µl	No of meas. values	: 5
100.30	99.88	100.15	99.88	99.99	

Mean value		:	100.04	µl	Lim. val. (manuf./user)	Status
Inaccuracy	(d) :		0.04	%	± 1.00 %	OK
Imprecision	(CV) :		0.18	%	≤ 0.30 %	OK

Meas. ser.	: 3	Meas volume	: 200.00 µl	No of meas. values	: 5
200.6	200.5	200.4	200.3	200.6	

Mean value		:	200.5	µl	Lim. val. (manuf./user)	Status
Inaccuracy	(d) :		0.25	%	± 0.60 %	OK
Imprecision	(CV) :		0.07	%	≤ 0.20 %	OK

Serviced

Parts used: none

Adjustments: slight adjustment downward

Humidity (rh): 63%

Temperature	: 21.70 °C	Air pressure	: 1,010.00 hPa	bidistilled water
Density	: 0.9979891 mg/ul		Correction value Z	1.0031000 µl/mg
Calibrated with	: Mettler SAG 1120062639 (Onlinemessung)			
Calibrated by	: Neil Abrams at 06/10/2010 15:07:44			
Remark	:			

Date printed : 07/10/2017 Signature

Key: (...) deleted values Page : 1 Vers.: 2.0/011114

Appendix 9: Turn-it-in Digital Receipt

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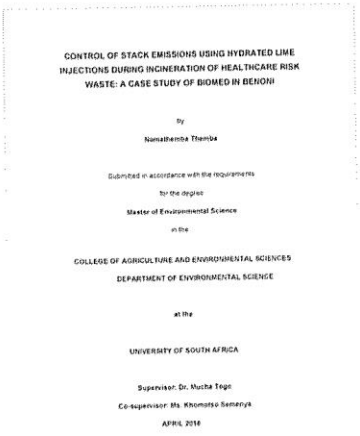

CONTROL OF STACK EMISSIONS USING HYDRATED LIME INJECTIONS DURING INCINERATION OF HEALTHCARE RISK WASTE: A CASE STUDY OF BIOMED IN BENONI

by

Nomalhemba Themba

Submitted in accordance with the requirements

for the degree

Master of Environmental Science

in the

COLLEGE OF AGRICULTURE AND ENVIRONMENTAL SCIENCES

DEPARTMENT OF ENVIRONMENTAL SCIENCE

at the

UNIVERSITY OF SOUTH AFRICA

Supervisor: Dr. Mucha Tego

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